# 3D VISUALIZATION FOR CULTURAL HERITAGE DOCUMENTATION: A Case Study of the Old PC's Office Building in Nairobi.

By

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# DECLARATION

This thesis is my original work and has not been submitted for a degree in any other University.

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# ABSTRACT

The old Provincial Commissioner's (PC's) office building in Nairobi forms the case study in this thesis. The currently available form of visualization for this monument at the National Museums of Kenya (NMK) is in the form of a (2-D) survey plan. The basic objective of this study is to develop a methodology for creating a 3-D model of the above monument, which can also be extended and applied to similar monuments.

The specific tasks undertaken to meet this objective can be summarized as follows: provision of photo control; close range image acquisition; photogrammetric processing of the images; 3D modelling from resulting photogrammetric solution; laser scanning; 3D modelling of the laser scan data; data fusion of the line model from photogrammetry with the line model from laser scan; and finally draping of the laser scan surface model with artificial computer generated texture.

The results of the 3D line model from photogrammetry were not satisfactory. However, the stitching of the laser scan data using Cyclone™ 3.0 software was done successfully, as well as the 3D surface model and the 3D line model using both AutoCAD 2002 and Golden Surfer 7.0. The fused 3D line model did not align perfectly. Nonetheless, the fused model shows that there is more to be gained in using both mapping technologies in the documentation of cultural heritage monuments.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| 2D | 2-Dimensional |
| 3D | 3-Dimensional |
| CAD | Computer Aided Design |
| CBD | Central Business District |
| CCD | Charge-Coupled-Device |
| CHIS | Cultural Heritage Information System |
| CRP | Close Range Photogrammetry |
| DSM | Digital Surface Model |
| DTM | Digital Terrain Model |
| GDI | Geospatial Data Infrastructure |
| GIS | Geographic Information System |
| GK | Government of Kenya |
| ICOMOS | International Council of Monuments and Sites |
| ISPRS | International Society for Photogrammetry and Remote Sensing |
| KANU | Kenya African National Union |
| NMK | National Museums of Kenya |
| PC | Provincial Commissioner |
| RMS | Root Mean Square |
| UNESCO | United Nations Educational, Scientific and Cultural Organization |
| UTM | Universal Transverse Mercator |

# 1. INTRODUCTION.

This chapter introduces the work presented in this thesis. Contained therein is a brief summary of the background to the study. The statement of the problem addressed in the study, together with the objectives, and the organization of the thesis are presented at the end of the chapter.

## 1.1 Background to the Study

Microsoft Encarta Encyclopaedia (2002) defines architecture as the art or science of designing and constructing buildings with durable materials following certain canons, to produce structures that are suited to their purpose, and that are visually stimulating and aesthetically pleasing. Studying the architecture of buildings provides one way of appreciating the culture and heritage of a society. Furthermore, even within a society, different generations will demonstrate differing architecture depending on what they value and uphold as their culture and heritage at the time. Hence, imbued with a message from the past, historic monuments of past generations remain at the present day as living witnesses of their aspirations, intrinsic cultural and heritage values ICOMOS (International Council on Monuments and Sites, 1964). These cultural monuments need to be preserved for future generations in order to be presented to them in the full richness of their authenticity.

Through the expansion of infrastructure and occupation of extensive areas by industrial, commercial and residential buildings, many cultural sites and monuments are in danger of either being destroyed or disfigured, thereby erasing stylistic characteristics and expressions of the past Renuncio (2001). This has made it necessary for governments to put in place policies that support preservation and conservation of historic sites, monuments, and artefacts. Ideally, such policies should also foster careful management of resources and promote balanced growth and development.

In Kenya, the government has institutionalized two Acts of Parliament in a bid to support the preservation of both its culture and heritage. The first one is the Antiquities and Monuments Act, Chapter 215 of the Laws of Kenya GK (1984a). This Act, last revised in 1984, provides for the preservation of antiquities and monuments. Enacted together with this was the National Museums Act, Chapter 216 of the Laws of Kenya GK (1984b). Also last revised in 1984, this latter Act provides for the establishment, control, management and development of National Museums. The National Museums of Kenya (NMK) is responsible for the management of museums in the country. It is also charged with the responsibility of ensuring the gazettement, protection and preservation of structures which are of historical, archaeological, palaeontological, geological, religious and/or cultural significance to Kenya.

Even with the above legal framework in place, the preservation and restoration of historical sites and monuments continues to face many challenges Habitat (1989). The first challenge remains lack of awareness amongst the general population of the need to preserve their cultural heritage. This has necessitated the need to foster awareness of Kenya's culture and heritage, thereby generating public interest in its conservation. The second main problem is the lack of adequate architects, planners, surveyors, engineers, technicians, and crafts personnel trained in restoration and preservation (of historic sites, monuments, and artefacts) in the NMK. Thirdly, many heritage resources are lost due to physical deterioration brought about by inadequate maintenance or by simple neglect; often this is because of lack of adequate financial resources. Kenya, being a typical developing country, is grappling with a myriad of problems with limited resources available to address them all. Cultural preservation is expensive, and yet the government is expected to cater for the many gazetted sites and monuments, that all need immediate attention. As a pragmatic solution to this problem, the government should encourage organizations and stakeholders to invest in culture by providing them with attractive incentives and offering rebates for doing so (NHWO (1999), Renuncio (2001)).

Notwithstanding the challenges above, Kenya has many remarkable cultural sites and monuments. The most notable is clearly the coastal town of Lamu. It was designated as a United Nations Educational, Scientific and Cultural Organization (UNESCO)

World Heritage Site in December 2001 Jordan (2003). Referred to as the 'Jewel of the Indian Ocean', Lamu has been, and continues to be a centre of Swahili civilization. Its buildings are characterized by a unique coral architecture. This tradition has been maintained through a conscious effort on the part of the residents. It is unfortunate that many of the towns in Kenya cannot claim a unique architecture in the design and construction of its buildings. Besides, it is common to mistake one town for another due to the similarities in the built-up areas. With the older buildings bearing great resemblance to those built by the colonialists (e.g. Kenya National Archives in Nairobi), and the modern sky-scrappers similar to those adorning major cities worldwide. The culture of many developing countries is no doubt being re-defined by that of their western counterparts. It appears as though the future of globalization will also see the melting of the diverse cultures into one common culture and heritage for all peoples. In order to avoid loosing its identity wholly, it is important that developing countries in general safeguard their architectural heritage as living testimonies of their age-old traditions.

Despite the rich culture and heritage of many Kenyan historical sites and monuments, many of these landmarks still lack proper documentation. For a long time, NMK has maintained a paper-based, largely textual, database of prehistoric and historic archaeological sites and monuments. Such a system has numerous inconveniences when it comes to sharing of information with other stakeholders. There is need to develop a digital database for the proper management of historical sites and monuments, providing maximum flexibility of storage and access to data. Perhaps it is with this in mind that the NMK is now in the process of creating a Geographic Information System (GIS) database of Kenya's archaeological sites and monuments. This database will contain various attributes of the sites, as well as photographic images of the same. However, the database on Nairobi's monuments contains only text information.

Article 16 in ICOMOS (1964) states that in all works of preservation, restoration, or excavation, there should always be precise documentation in the form of analytical and critical reports, illustrated with drawings and photographs. In this regard, restoration is defined as a highly specialized operation whose main aim is to preserve and reveal the aesthetic and historic value of the monument, based on respect for original material and authentic documents.

Given that a monument can be conserved and restored only when it has been mapped and documented periodically, there is a need to provide cost effective and versatile methods for mapping historical monuments (Fellbaum (1992), Renuncio (2001)). The modern digital techniques have led to novel systems, processing methods and results that can generate 3-D spatial representations in no time Hanke & Grussenmeyer (2002). This geospatial information can be incorporated into a GIS to support cultural and heritage management. Such an information system should be easily accessible by a remote user, with a facility to visualize, navigate, execute scenario predictions in the historical sites, query and generate custom-tailored reports (Whiting & Nickerson (1997), Boehler & Heinz (1999), Renuncio (2001)).

Previously, historical sites and monuments were documented using manual field measurements, which were both labour intensive and time consuming. The aspect of using digital technology to capture the same information is more appealing in terms of economy since the cost of mapping is significantly reduced. In addition, a lot more information is captured using digital techniques, which is not easily captured using other techniques. Such information enhances the recognition of the type and texture of tiles, marble incrustations and other decorative elements used in the construction of these buildings, their spatial distribution and conditions Chong *et al* (2003). These are some of the most difficult and time-consuming tasks faced by architects, conservation experts and photogrammetrists in heritage site recording Renuncio (2001).

Further, once the images have been acquired, measurements can be done on them repeatedly at no additional data acquisition costs. Digital image processing techniques combined with advanced 3-D modelling techniques provide powerful 3-D visualizations of these sites and monuments, which are effective for preservation and conservation exercises, as well as internet transmission and electronic promotion as in the case of virtual museums.

## 1.2 Statement of the Problem

For many of the historical monuments, such as the old Nairobi PC's building, most measurements are still made using traditional surveying methods and are documented in 2-D drawings in the form of analogue plans. Extracting information from such plans is restrictive and limiting for majority of the people who are not accustomed to working with 2-D drawings. One needs some basic understanding of 2-D plans, whether through formal or informal training, in order to correctly interpret them. Human beings view and interact with objects in the real world in 3-D; hence extracting information from a 3-D model is much easier and more natural than extracting the same from a 2-D equivalent. With a 3-D model, it is possible to drape its surface with texture obtained from the photographs thus giving it a more "photo-realistic" appearance.

In Kenya, 3-D visualization applications have found their way in advertisements, architectural and engineering applications, and computer games amongst others. Use of 3-D visualizations as part of the documentation of heritage sites and monuments is yet to be realized. This is despite the fact that this facility allows one to use the data in much more exciting and creative ways. A probable major hindrance to the adoption of 3-D visualization is the incorrect assumption that the product of any surveying exercise should be static and usually in the form of a paper map. A 3-D visualization can provide a unique perspective to the user by allowing one to "fly or walk" around and within the sites and monuments (animations), and view or analyze the surrounding landscape from different perspectives. This is otherwise unattainable when using 2-D analogue maps.

As outlined in section 1.1, proper documentation of virtually all historical sites and monuments in Kenya is yet to be accomplished. More should be done in a bid to remedy this grave situation, particularly if an appropriate framework for cultural and heritage conservation and restoration is to be developed. This study attempts to address this problem by seeking to introduce the idea of employing 3-D visualizations as an integral part of the documentation of historical sites and monuments in Kenya.

This form of visualization is very important, particularly in the preservation and restoration of ruined heritage sites where architects and renovation experts must have a realistic view of the ruin. As discussed in section 2.1, virtual tourism provides a means for tourists to access remote, inaccessible, fragile, or closed cultural and natural heritage sites, while simultaneously protecting them from physical damage. 3-D visualizations when transacted over the Internet, form an excellent marketing tool that may stimulate a viewer to experience the "real thing" NHWO (1999).

## 1.3 Objectives of the Study

The main objective of this study is to develop a methodology for creating a 3-D model of the old PC's office building. This study has confined itself to mapping, representation and visualization of the building using close range photogrammetry and laser scan technology. Although it is possible to create an interactive dynamic virtual representation (animation) of the monument that could facilitate a virtual tour of the building, such an aspect is not considered in the study.

In order to realize the above objective, the following tasks are performed:

- provision of photo control;
- acquisition of overlapping digital close-range images;
- obtaining a photogrammetric solution from the close-range images;
- 3D modelling using close-range photogrammetry;
- laser scan survey of the building;
- 3D modelling of the laser scan data;
- data fusion of the line model obtained from the photogrammetric solution, and the line model obtained from the laser scan data.

## 1.4 Organization of the Thesis

The second chapter presents an overview of documentation and management of cultural heritage. Chapters three and four examine two modern mapping technologies available for the documentation of cultural sites and monuments, and highlight the advantages of integrating the two techniques. Chapter five outlines the processes involved in the 3D modelling of the old PC's office building using both close range photogrammetry and laser scan data. It also provides a detailed discussion of the results obtained. Chapter six presents the conclusions and recommendations of the study.

# 2. DOCUMENTATION AND MANAGEMENT OF CULTURAL HERITAGE.

The subject of documentation is broad. This chapter gives an overview of the relationship between sustainable tourism and cultural heritage management. Also given is a brief definition of documentation, together with an example of the type information may be contained in a classical conventional documentation. The need to share this information with others necessitates the requirement for an integrated information system that will provide the framework for sharing this information with all those interested in cultural heritage.

## 2.1 Sustainable Tourism and Cultural Heritage Management

Heritage is a broad concept and includes the natural as well as the cultural environment ICOMOS (1999). It encompasses landscapes, historic places, sites and built environments, as well as bio-diversity, collections, past and continuing cultural practices, knowledge, and living experiences. It records and expresses the long processes of historic development, forming the essence of diverse national, regional, indigenous, and local identities and is an integral part of modern life.

A mutual dependence exists between tourism and cultural heritage. Tourism depends heavily on the attractions of natural and cultural heritage, diversities, and living cultures, thereby generating considerable amounts of foreign exchange that can be used to finance the conservation and management of cultural and natural heritage (Shemdin-Simison (1994), ICOMOS (1999) & NWHO (1999)). In addition, the tourism industry has the potential to create jobs for the host communities living near the heritage sites, thereby directly addressing issues relating to poverty and unemployment. Such an action can greatly enhance the much-needed public support for the preservation of the heritage sites.

Unfortunately, without proper planning and management, tourism can have a negative impact on the heritage sites, through physical degradation. This is especially critical for heritage sites that are perceived to be fragile in nature. For such sites, banning or limiting the number of visitors to the site would have a negative influence on the tourism industry. A more viable solution would be to create virtual museums that would facilitate a virtual "tour" of such sites without causing any physical damage to the same. The virtual tours can also be useful for marketing other tourist destinations that are not very popular, as a means of reducing pressure on the more vulnerable well-known popular sites.

The challenge, therefore, in sustainable tourism and cultural heritage management is in managing the future growth of the industry (tourism). This growth should minimize its negative impacts on the environment and host communities whilst maximizing the benefits it brings in terms of jobs, wealth and support for culture and industry, and protection of the built and natural environment NHWO (1999). It should also provide equitable economic, social, and cultural benefits to the men and women of the host or local community, at all levels, through education, training, and the creation of full-time employment opportunities. This is based on the assumption that the appropriate legislative and institutional frameworks are in place and that proper planning and coordination amongst the various stakeholders has been carried out. The institutional framework should also include policies that aid in the identification and protection of heritage resources.

Hence, before heritage places are promoted or developed for increased tourism, management plans should assess the natural and cultural values of the resources ICOMOS (1999). Thereafter, they should establish appropriate limits of acceptable change, particularly in relation to the impact of number of visitors on the physical characteristics, integrity, ecology, and bio-diversity of the place, local access, and transportation system, and the social, economic, and cultural well-being of the host community.

## 2.2 Documentation, Preservation, and Conservation of Built Heritage

The first attempt to establish a coherent and logically defensible philosophy for building conservation was in the Society for the Protection of Ancient Buildings (SPAB) Manifesto of 1877. The Venice Charter (ICOMOS, 1964), which was adopted by the newly formed International Council on Monuments and Sites (ICOMOS) in 1956 and published in 1966, formed an important modern milestone for the conservation movement Cultural Heritage Charters and Standards (2004). To date, there is a plethora of literature on the subject of documentation, preservation, and conservation of built heritage, which base their principle on the Venice Charter.

The documentation of built heritage involves the acquisition and storage of attributes (tangible or intangible), which portray architectonic characteristics, state of conservation, history, and geometry in some level of detail that depends on the historic importance of each monument Renuncio (2001). Given that documentation is one of the principal ways available to give meaning, understanding, definition, and recognition of the values of the cultural heritage, ICOMOS (1996) gives the following as valid reasons for documentation:

- to acquire knowledge in order to advance the understanding of cultural heritage, its values and its evolution;
- to promote the interest and involvement of the people in the preservation of the heritage through the dissemination of recorded information;
- to permit informed management and control of construction works and of all change to the cultural heritage;
- to ensure that the maintenance and conservation of the heritage is sensitive to its physical form, its materials, construction, and its historical and cultural significance.

Further, the documentation should be undertaken to an appropriate level of detail in order to:

- provide information for the process of identification, understanding, interpretation and presentation of the heritage, and to promote the involvement of the public;
- provide a permanent record of all monuments, groups of buildings and sites that are to be destroyed or altered in any way, or where there is risk from natural events or human activities;
- provide information for administrators and planners at national, regional or local levels to make sensitive planning and development control policies and decisions;
- provide information upon which appropriate and sustainable use may be identified, and the effective research, management, maintenance programmes and construction works may be planned.

With the built heritage well documented, its conservation is always facilitated by making use of it for some socially useful purpose ICOMOS (1964). Such use, though desirable, must not change the layout or decoration of the heritage, with only permissible modifications to facilitate the change of function.

### 2.2.1 <u>Types of Data Acquired in Documentation</u>

Knowledge of a built heritage requires information on its conception, its construction techniques, on the processes of decay and damage, on changes that have been made, and finally on its present state (see e.g. ICOMOS (2001), ICOMOS (2003)). Such knowledge entails:

- Definition, description, and understanding of the building's historic and cultural significance;
- A description of the original building materials and construction techniques;
- A historical research covering the entire life of the structure including both changes to its form and any previous structural interventions. Knowledge of what has occurred in the past can be of help in

predicting future behaviour and can be a useful indicator of the level of safety provided by the present state of the structure;

- A description of the structure in its present state including identification of damage, decay, and possible progressive phenomena, using appropriate types of tests. Here, the safety of the building is ascertained;
- Description of the actions involved, structural behaviour and types of materials.

Details on how to assess structural damage, materials decay, as well as a description of the possible remedial measures are well documented in ICOMOS (2001).

### 2.2.2 Cultural Heritage Information System

In keeping abreast with the changes in technology, the documentation of each site can be input into a Geographic Information System (GIS) database. A GIS contains both the spatial and non-spatial attributes, making it possible to combine both graphical and alphanumeric data in a database. It provides a more structured way of monitoring renovations, alterations, and inspections of the sites.

By making use of multimedia, it is possible to combine 3D visualizations (e.g. 3D models, animations, or Virtual Reality Modelling) of the site as part of the documentation, and accessing these through hyperlinks in the map. Where it is not possible to store the 3D visualization as part of the documentation, such as lack of sufficient computer storage space, it is possible to create detailed 3D models if the following set of basic data are stored as part of the documentation:

- A set of digital imagery of acceptable geometric and radiometric quality;
- A coordinate list of accurate ground control;
- Details of the imaging system;
- A topographic map showing the heritage site layout;
- Laser scan cloud points, where appropriate.

In addition, the following data could also be included: available photographs, detailed 2D drawings, solid models, surface models, line models, etc. Some key attributes may include the name and type of building, address, construction period, present day function, description (which may include type, façade, form of roof, building material, composition, ornaments, etc), history of the building, utilities supported, technical condition, protection system, and conservation.

The GIS databases for the various sites should be networked together to form a comprehensive web-based Cultural Heritage Information System (CHIS). In order to enhance data compatibility amongst the different databases within the CHIS, a set of standards should be strictly adhered to. Sharing of information is critical in heritage management. As such, the CHIS as a system would provide a forum that offers easy access to cultural heritage information by all the various stakeholders in Government, museum staff, archaeologists, tourism operators, local community, and academia amongst others. In Kenya, this would be a significant contribution in the management of cultural heritage sites and monuments, since currently majority of the information is often disparate, largely paper-based, and thus time consuming to retrieve. Moreover, relatively few people are aware of available sources of information.

# 3. CLOSE RANGE PHOTOGRAMMETRY.

This chapter provides a brief discussion on close range photogrammetry, as one of the modern technologies available for the documentation of cultural sites and monuments. An overview of the basic steps that are important in the implementation of a typical close range photogrammetric project is also given.

## 3.1 General Remarks

Information about objects is obtained remotely, with no need for physical contact, making photogrammetry a cost-effective method for precise recording of complicated architectural designs. It is from this that a resolution adopted in Washington, at an ICOMOS meeting held in 1987, recommended that all documentation of heritage sites (worldwide) be done using photogrammetry.

In photogrammetry, measurements are done on the images, as opposed to the objects directly. The advantages of this are threefold. Firstly, this removes the need to physically access each point to be measured, as is the case in conventional field measurements. Secondly, the measurements are carried out in the office, thereby reducing the time spent in the field to that necessary for the photography to be taken. Consequently, the costs involved are less, making it an accurate, cost-effective technique for collecting field measurements of any object or scenery. Lastly, measurements on the images can be done repeatedly at no extra cost, with no need for the fieldwork to be done afresh. Furthermore, if the photography is taken periodically, photogrammetry can also facilitate the analysis of qualitative and quantitative changes in an object over a period of time.

In close range photogrammetry, the images are often captured from a ground-mounted camera, whose distance from the object does not exceed 100m, whereas, in aerial photogrammetry, images are captured from airborne-mounted cameras (or digital sensors). Aerial photogrammetry is well known for the production of topographical or thematic maps, digital terrain models (DTMs), digital surface models (DSMs), orthoimages, 2D and 3D reconstruction and classification of objects. On the other hand, close range photogrammetry has found numerous applications in diverse fields such as architecture and civil engineering (to supervise buildings, document their current state, deformation or damages, etc), archaeology, medicine (e.g. plastic surgery), accident reconstruction etc.

## 3.2 Image Acquisition

**Imaging Sensors**

Photogrammetry, like many other scientific disciplines, has been revolutionalized by the recent changes in digital technology. Through this paradigm shift, it is now possible to not only capture the images in a digital form, but to also process the same using digital techniques. This has led to the concept of digital photogrammetry. Digital images can be directly obtained from digital sensors, or through the scanning of photographs captured on film cameras. The scanning process converts the latter into a computer-compatible format through the process of digitization. In addition, video cameras are also proving to be useful in the capture of data that is dynamic in nature, a good example being an explosion.

In order to simplify image acquisition, software packages for close range photogrammetry can process images captured by metric, semi-metric, or non-metric cameras. These software come with a camera calibration module that contains both self-calibration and on-the-job calibration capability. In addition, the imaging geometry does not have to be restrictive as the photographs can either be convergent, horizontal, vertical, or even oblique. Furthermore, these can also be taken at different times and using different cameras, depending on the situation at hand (Gruen (1978), Hanke and Grussenmeyer (2002), Chong *et al* (2003)).

Whether camera or video, these digital sensors have proven to be more efficient and reliable for capturing images in photogrammetry, as they provide an easier (and faster) way of acquiring images that can be directly downloaded, and then processed in a computer within a relatively short time. The new technology now employs the use of charge-coupled-devices (CCDs) in the design of the digital sensors. Hanke and Grussenmeyer (2002) list the following as some of the advantages of using digital images:

- direct data flow with the potential of online processing,
- high potential for automation,
- good geometric characteristics,
- independent of the film development process with its inherent limitations,
- direct quality control of the acquired images,
- low-cost system components.

**Establishment of Photo Control**

In the establishment of photo control, a network of ground control is obtained by running a traverse (i.e. a classical surveying technique). Thereafter, the geodetic control is transferred onto the building façade by making use of tacheometry. The control points on the building should include well-defined points such as corners of the building, windows, doors, or special targets strategically placed on the building façade. These points are aptly selected to uniformly cover the different sides of the building, thereby adequately solving the basic datum problem Fraser (2001).

Where desirable, such control points can be used to geo-reference the final 3D model into the national geodetic reference system. This is particularly useful when the 3D model needs to be overlaid with other data-sets such as a cadastral or topographical map, or even a high resolution remotely-sensed image. However, many national geodetic reference systems are characterized by large coordinate values (e.g. UTM coordinates). These large coordinate values, in turn, increase the amount of storage space required significantly, as well as increase the processing time for the various algorithms that are required to process the 3D models. Therefore, often a local datum will suffice in most close range photogrammetric applications.

**Photography**

Rarely will a single pair of overlapping photographs offer sufficient coverage of large monuments, such as buildings or heritage sites. For such objects, the number of photographs necessary to provide complete coverage depends on the object's size, shape, as well as the complexity (or simplicity) of its design. However, the most important consideration during the photography is the imaging geometry to be employed. Within the framework of first-order design in the optimization of close range photogrammetric networks, the convergent imaging geometry is mandatory. This ensures that a near-homogenous distribution of object point precision is obtained Fraser (2001).

## 3.3 Photogrammetric Solution

More often than not, a typical close range photogrammetric process may comprise of four basic modules (steps). The first is the fieldwork, which involves establishment of ground control points and the actual photography. Thereafter, the images are processed accordingly, depending on whether they are digital or film-based. Once the image processing is satisfactory, the photogrammetric solution is obtained using the bundle adjustment process (Gruen (1978), Karara *et al* (1980), Moffit and Mikhail (1980)). The presentation of the final photogrammetric results can be in the form of a set of coordinates, 2D plans, or 3D models.

### 3.3.1 Image Pre-processing

The current generation of cameras available for close range photography have good characteristics that ensure that images are captured with minimum geometric and radiometric distortions. For such images, basic image processing algorithms are necessary to perform image transformation, rectification and enhancement, especially if the images will be used to drape surfaces of the 3D models.

### 3.3.2 Photogrammetric Solution using Bundle Adjustment

The culmination of many CRP projects is a 3D model, which can either be an end product in itself (say for visualization), or can be exported to other CAD (Computer Aided Design) software for further processing. Digital CRP software uses the bundle adjustments techniques to compute the 3D coordinates of points selected to define the 3D model of an object. Once the 3D model has been created, these software also have algorithms that use surface texture obtained from the photographs to drape the surface of the 3D model to create a 'photorealistic' 3D model. The digital CRP software that uses the mono-scopic multi-image measurement systems, such as PhotoModeler, eliminates the need to view in stereo for high accuracy plotting.

As input in the photogrammetric solution, the images together with *à priori* information on the camera calibration parameters (i.e. the calibrated focal length, the position of the principal point, as well as the coefficients of the polynomial describing the lens distortion) are loaded into the software. Where the camera calibration parameters are unknown, general details of the camera such as the focal length and the format size of the images can be used to perform an on-the-job calibration of the camera simultaneously as the photogrammetric solution is being carried out. The calibration of the camera ensures an accurate reconstruction of the bundle of rays that existed at the time of photography (i.e. interior orientation).

With the images loaded into the software, the next step involves selecting points on the images to be used as input in the bundle adjustment. The selected points should uniformly cover the overlap areas between photographs in order to provide a strong geometric configuration that will facilitate the photogrammetric restitution. These measured photo coordinates are processed simultaneously, using least-squares based on collinearity equations, to determine interior orientation elements (or camera calibration data in the case of self-calibration), exterior orientation elements, model space coordinates, and object (ground) space coordinates (i.e. absolute orientation). See Appendix C for a brief description of the mathematical formulations in close range photogrammetry.

The bundle adjustment method is advantageous due to the following reasons (Karara *et al* (1980), Hanke & Grussenmeyer (2002)):

- it allows orientation in one step, as opposed to the 2-steps (relative orientation and absolute orientation);
- it ensures a simultaneous solution of all the photographs orientation, thereby providing a homogeneous solution for the entire building;
- offers an on-the-job calibration of the camera (useful for non-metric cameras);
- flexible concerning the geometry of the camera positions, and;
- can accommodate photography of any kind.

# 4. LASER SCAN TECHNOLOGY

This chapter offers a basic introduction into the laser scanning technology. The principles of laser scanning, together with the various processes that go into creating a 3D model using laser point cloud data are discussed herein.

## 4.1 Principles of Laser Scanning

Up until about a decade ago, photogrammetry was the only technology associated with the determination of an object's coordinates from the geometry provided by the object being imaged in two or more different photographs. With the recent advances in laser scanning technology, it is now possible to perform the same through laser scans. Laser scanning, initially used in industrial plants, has recently found use in the documentation of architectural sites and monuments.

In principle, these scanners make use of laser beams (rays) to determine the 3D coordinates of an object. During the scanning process, the rays are projected across the object's surface, with the scanning effect being achieved by using one or two mirrors that allow changes of the deflection angle in small increments Boehler *et al* (2001). A combination of these angular settings together with the distance measurements are used to determine the reflecting position. Laser scanners resolve distance measurements based on either the "pulse time-of-flight" or the "amplitude modulated continuous wave" principles (ranging scanners), or the principle of "triangulation" (triangulation-based scanners). A brief description of each of these approaches follows.

For the pulse time-of-flight scanner, a laser beam emitted at regular intervals is reflected back from the surface of the object. The distance of the surface from the scanner is resolved by making use of the speed of light and the pulse travel time (see Figure 4.1). The amount of signal reflected from the surface is dependent on the colour of the surface, the roughness of the surface, and the angle at which the surface is scanned (Baltsavias (1999a), Barber & Mills (2001), Fangi *et al* (2001), and

Thiyagarajan (2003)). The intensity value is a measure of the reflectance, and therefore supplies information about the spectral characteristics of the object. The basic formula of computing the distance measured using these scanners is given as follows (Baltsavias (1999a)):

$$R = c\frac{t}{2} \qquad \text{.......equation 4.1}$$

$$\Delta R = c\frac{\Delta t}{2} \qquad \text{.......equation 4.2}$$

where $R$ (m) is the range (distance between the sensor and the object), $\Delta R$ (cm) is the range resolution, $c$ (m/s) is the speed of light (~ 300,000,000 m/s), $t$ (s) is the time interval between the sending and receiving of a pulse (echo), and $\Delta t$ (s) is the resolution of the time measurement.

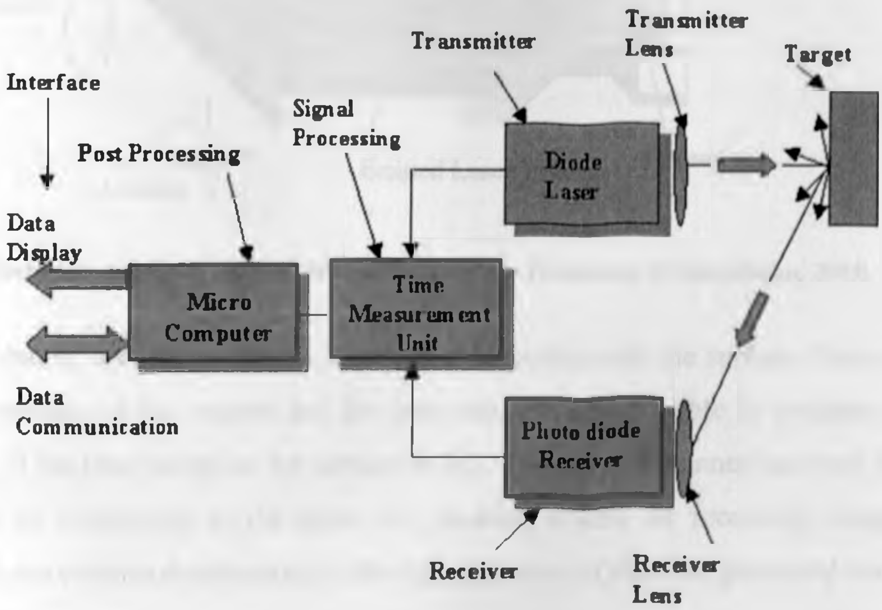



*Figure 4.1: Pulsed Time-of-Flight Technology (Thiyagarajan, 2003).*

Amplitude modulated continuous wave technology is also applicable in laser scanning. In this case, the emitted laser beam is amplitude modulated. The beam reflected from the surface is shifted in phase (see Figure 4.2), where the distance is directly proportional to the measured shift in phase. The basic formula for computing the distance measured by this type of scanner is given as (Baltsavias (1999a)):

$$R = \frac{1}{4\pi}\frac{c}{f}\varphi \quad \text{......equation 4.3}$$

$$\Delta R = c\frac{\Delta t}{2} \quad \text{.......equation 4.4}$$

where $R$, $\Delta R$, $\Delta t$ and $c$ are as described earlier, $f$ (Hz) is the frequency, and $\varphi$ (rad) is the phase.

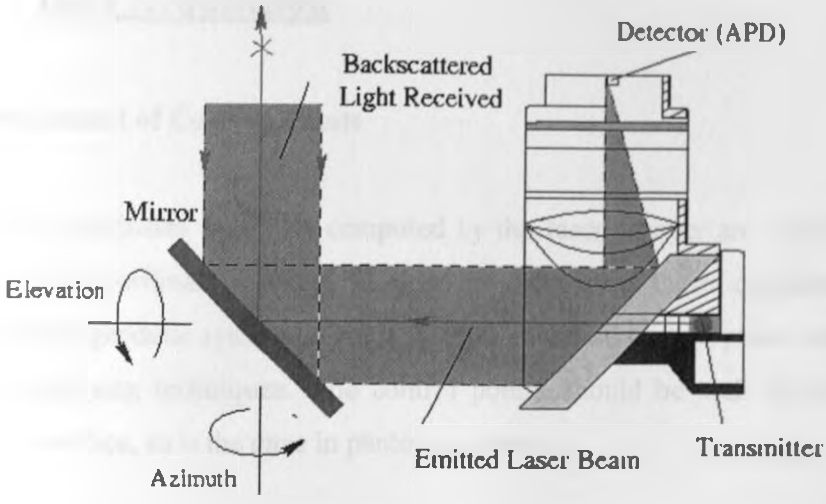



*Figure 4.2: Amplitude Modulated Continuous Wave Technology (Thiyagarajan, 2003).*

In triangulation, a camera views a laser beam projected onto the surface. From the known positions of the camera and the laser emitter, it is possible to compute the positions of the laser beam on the surface in 3D. This type of scanner has very high resolution in comparison to the other two, making it ideal for recording complex structures. An obvious disadvantage is the large amounts of data sets generated during the scanning process.

The use of lasers (as is the case in photogrammetry) can be inhibited by the presence of people within the area, rain, dust, or fog. Even with these limitations, laser scanning equates to a much higher productivity in comparison to tacheometric and photogrammetric surveying Boehler *et al* (2001). To illustrate the high speeds of data acquisition using laser scanner, a *Cyrax 2500* laser scanner can generate 14,400 points per second. With such high speeds, a complete geometry of an object is remotely captured within minutes in the form of dense, accurate "3D point clouds", ready for immediate use. This aspect makes it more desirable, in comparison to photogrammetric surveying, since in the latter, images are needed before measurements can be executed. However, it should be noted that the accuracy of geodetic instruments is far superior to laser scanners, and as such the scanners should never replace measurements currently carried out by these Boehler *et al* (2001).

## 4.2 Data Acquisition

**Establishment of Control Points**

The 3D coordinates of points computed by the laser scanner are with respect to its own local coordinate system. In order to transform these coordinates into the appropriate geodetic system, there is need to establish control points within the area using surveying techniques. The control points should be well distributed on the object's surface, as is the case in photogrammetry.

**Scanning**

Depending on the complexity of the object, it is often necessary to take multiple scans from different positions around the object to ensure complete coverage. This is similar to photographing an object from different perspectives in order to achieve complete coverage necessary for processing the data using photogrammeric techniques. In most cases, the laser scanner has a digital camera whose purpose is to orient the scanner in the desired direction, so that adjacent scans have a sufficient degree of overlap. The resolution of the images captured by the laser scanner's inbuilt digital camera is very low in comparison to images captured by other digital cameras.

## 4.3 Point Cloud Data Processing

### 4.3.1 Image Registration

Each laser scan captures a portion of an object's surface. In order to view the entire object in 3D, the different scans are knit (or stitched or aligned) together to create a continuous 3D model. This stitching process, where all the different laser scan point cloud data are transformed into a single coordinate system, is referred to as image registration. It is a process that involves identifying common points (i.e. tie points) in each overlapping point cloud and transforming them into a single coordinate system using a six-parameter, rigid-body transformation Gordon *et al* (2001).

The manner in which the image registration is carried out in a point cloud data processing software depends on whether common points are targets or features on the object (e.g. corners). These targets are specifically designed to be highly reflective, and can either be flat or spherical in shape. In the presence of targets, the software has algorithms that readily identifies them (with the help of the operator), and uses these to register the different laser scans into the same coordinate system.

However, in the absence of targets, features that are common in the overlap areas can be used to match the adjoining point cloud data sets. These features should be well defined and easily recognizable in the overlap area of both laser scans. They can include, but are not limited to, corners, grids patterns and/or alphanumeric characters. To minimize errors during the matching process, the feature points selected in the two (adjoining) laser scans should match each other as closely as possible (Cyclone™ 3.0 software sets this distance to within 10cm – Cloud Registration Maximum Search Distance). Since this method involves visualizing and matching up corresponding pairs of dots, it is quite tedious and error prone given that a single scan can have points totalling to hundreds of thousands.

### 4.3.2 Point Thinning

Once the registration has completed successfully, the next step is the removal of irrelevant points from the cloud data. Such points may include (second pulse) reflections from objects in the background, reflections from objects (e.g. trees) in the space between the scanner and the target, amongst others. This significantly reduces the file size and lowers the processing times for modelling algorithms. This is necessary since the files created during the image registration are large; with each processing step being time-consuming and requiring maximum computer processing power (Gordon *et al* (2001) and Vozikis *et al* (2004)).

### 4.3.3 Surface Modelling

At this point, the final registered 3D model still comprises of a collection of closely spaced dots that have been coordinated in xyz, together with their corresponding intensity values. The process of fusing these dots into a single shape, say by fitting primitives such as polygonal meshes on the dots, is what is referred to surface reconstruction (or surface modelling). The surface created is an estimated curve that follows the shape (of the object) and is very close to the points Cureless (1999).

### 4.3.4 Surface Rendering

In order to give the 3D model a "realistic" look, its surface is usually draped with texture (i.e. texture mapping) that could be obtained from photographs. These photographs, ideally, should be acquired using a camera that is located as closely as possible to each scanner location, so that it captures images that correspond (as nearly as possible) to the laser scan point cloud data. The camera can either be digital or film-based. These images are re-projected onto the 3D model, a process that may involve a new process for every small surface element to decide (based on the incidence angle) from which of the available images the information has to be taken Boehler *et al* (2002). Besides, radiometric corrections regarding brightness, contrast and colour balance may also be very difficult to apply since illumination conditions during image acquisition will never meet the precondition of being the same on every surface element Boehler *et al* (2002).

The surface rendering helps provide a more realistic view that proves useful for monuments and sites with a high level of surface detail, which would otherwise be too much detail for the line model. These models are also useful to those in the filmmaking industry, the proceedings of which can be channelled towards the preservation efforts.

## 4.4 Documentation Using Integrated Technologies

The documentation of historical landmarks would benefit immensely from the combination of both photogrammetry and laser scanning techniques. Each of these has its own strengths and weaknesses. Photogrammetry is a mature technology; one that depends more on software than hardware or firmware in comparison with laser scanning. Majority of the CRP software available in the market are flexible, in the sense that the images can be acquired using either digital or film-based cameras. These, in turn, can either be metric, semi-metric, or even amateur cameras. Also, most CRP software have similar functionalities, making it easy to switch from one software to another (Baltsavias (1999b), Hashemi & Reinhart (2001)).

Laser scanning, on the other hand, is a less mature technology than photogrammetry, which is highly dependent on hardware and firmware. Each laser scanner, when purchased, is supplied together with software that has been designed to specifically process its point cloud data. A small number of companies have developed stand-alone software for processing point cloud data. Nevertheless, these are limited when compared to the numerous stand-alone software that are available for close-range photogrammetry. Laser scanning systems differ in terms of cost, data collection, targeting and range, portability, hardware and electronics reliability, availability, and maintainability (Baltsavias (1999b), Hashemi & Reinhart (2001)). With photogrammetry, it is easier to model the edges on an object. Edge detection in laser scanning is problematic, even with the current software available for processing point cloud data. This is an area that is generating a lot of research. Also, the photographs used in photogrammetry are acquired instantaneously, making it suitable to capture data that is dynamic in nature. A laser scanner, on the other hand, takes time to complete data capture making it unsuitable for mapping such scenarios.

Laser scanners capture dense and accurate point clouds that are already coordinated in 3D and ready for immediate use, whereas in photogrammetry, images are needed before any measurements can be executed. Being an active system, laser scanners eliminate the need for ambient lighting like in photogrammetry, where even the scanning can be done in complete darkness if so desired (Baltsavias (1999b), Barber & Mills (2001)). Due to the high rates of data capture, a laser scanner takes a relatively short time to capture dense geometric details of an object and at a high resolution. The resulting files are large, which in turn creates difficulties when it comes to managing the information.

When combined effectively, these two technologies complement each other's weaknesses so that the resultant model captures much more information about the physical feature than when either is used independently. In this case, the laser scans can be fused with the resultant model obtained from photogrammetry to create geometrically correct, photo-realistic models, while opening up new areas of application (Baltsavias (1999b), Hashemi & Reinhart (2001), Forkou & Kirg (2003)). This is because photogrammetry provides high quality images with multi-spectral capabilities, while laser scanners give monochromatic images of inferior quality. These high quality images are very useful in creating 3D visualizations, simulations and animations Baltsavias (1999b). Hashemi & Reinhart (2001) caution that the two technologies should be combined using a proven and well-documented methodology, such as that proposed by Forkou & Kirg (2003).

# 5. RESULTS AND ANALYSIS.

This chapter offers a brief history of the study area, together with the proposed use of the monument by the National Museums of Kenya. An overview of the different types of 3D models is provided. An outline of the processes involved in 3D modelling of the building, using both photogrammetry and laser scanning is given. In the absence of software that specifically deals with point cloud data, the approach outlined in section 4.3 offers an alternative method of creating surface and line models using AutoCAD and Golden Surfer software. The last section of this chapter discusses the results obtained from fusing the line model from photogrammetry with the line model obtained from laser scanning.

## 5.1 Description of the Study Area

### 5.1.1 History of the Monument

In 1889, the engineers constructing the Uganda Railway decided to set up a base for the Railway's Headquarters at a place situated midway between the Port of Mombasa and Kisumu, which they named Nairobi Smart (1950).The name Nairobi comes from the Masai words '*enkare nyarobe*', which means sweet waters. The Masai used it as a watering place for their cattle. In the same year, the provincial administration under *Colonel Ainsworth* transferred its Headquarters from Machakos to Nairobi.

The old Provincial Commissioner's (PC's) office was among the first Government buildings in Nairobi (NMK (1999), Abungu (2001)). Built in 1913 in a classical architectural style, the Government Architect *C. Rand Overy* designed it to be an office for the Ministry of Native Affairs. This building, which is still in a remarkable condition, lies at the corner of *Kenyatta Avenue* and *Uhuru Highway* in Nairobi's Central Business District as illustrated in Figure 5.2. Here, it is enclosed within the *Nyayo House* precincts. Figure 5.1 shows the exterior of this building beautifully decorated with columns, frieze and pediment all built of natural stone. Its entrance leads to an octagonal shaped hall covered with a beautiful dome-shaped ceiling. The surrounding rooms branch off from this central space.

From 1913 up until 1983, the building accommodated the provincial administration offices. It also served as a birth, marriage and death-recording centre, which the settler community fondly referred to as "Hatches, Matches and Dispatches" (Oyaro (1999), Abungu (2001)). When the provincial administration offices were transferred to *Nyayo House* in 1983, the Government converted the building into a Nairobi KANU (Kenya African National Union) branch office, up until the time it was declared a National Monument in 1995.

***Figure 5.1: Photograph of the Old PC's Office Building.***

On 13$^{th}$ of April 1995, the building was gazetted as a National Monument in Kenya, through the Gazette Notice No. 2016. Thereafter, it was officially handed over to the National Museums of Kenya on 11$^{th}$ of October 1997. Being one of the oldest buildings that still grace the skyline of Nairobi, the Old PC's office building is no doubt a landmark monument of immense cultural and heritage value to Kenya.

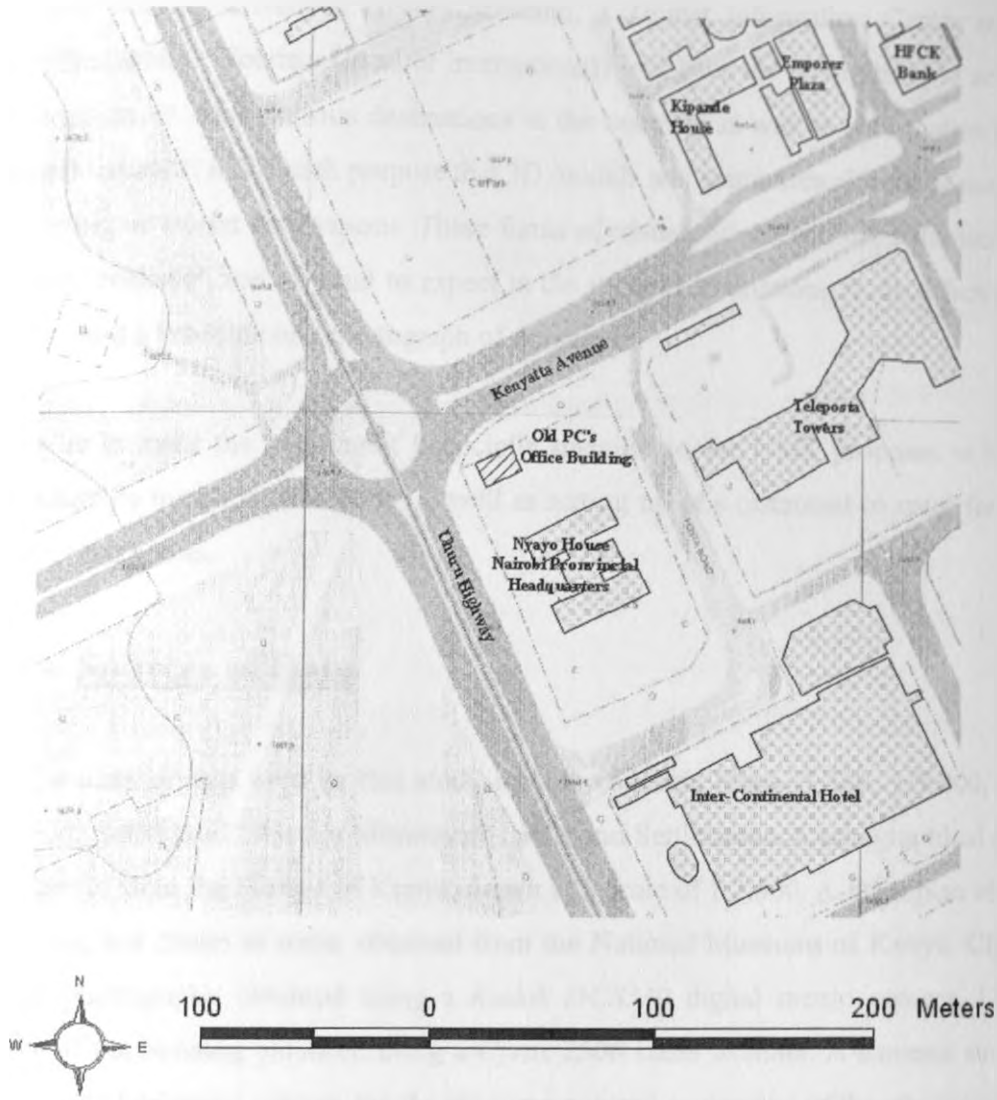



*Figure 5.2: The Old PC's Office Building on Scanned Topo Map.*

## 5.1.2 <u>Proposed Use of the Monument</u>

Restoration of the Monument is already underway, under the close supervision of the NMK. The renovation includes removing non-conforming additions, scraping and cleaning of all the walls and woodwork to restore them back to their original appearance, and any other structural repairs on windows and floors Abungu (2001).

Abungu (2001) further explains that the NMK, in consultation with other stakeholders, has established a concept for the future use of the monument, which includes housing a Nairobi History Museum, a Tourist Information Centre and a Café/Restaurant. Tourists (local or international) will have the opportunity to access information on other various destinations in the country, as well as information of a general nature. It is for such purpose that 3D models and animations should be used in marketing of tourist destinations. These forms of visualizations will offer the tourists a more "realistic" feel of what to expect in the various destinations, more effectively than would a brochure or a photograph of the same.

In order to make the monument financially sustainable, the NMK proposes to lease out some its rooms to exhibitors, as well as setting up of a restaurant to cater for the anticipated guests.

## 5.2 Sources of Data

The sources of data used in this study include cadastral plans (1:500, 1:1,000, and 1:2,500), purchased from the Ministry of Lands and Settlements. A topographical map of Nairobi from the Survey of Kenya, drawn at a scale of 1:2,500. A floor plan of the building, not drawn to scale, obtained from the National Museums of Kenya. Close-range photography obtained using a *Kodak DCS330* digital metric camera. Laser scans of the building procured using a *Cyrax 2500* Laser Scanner. A traverse survey to provide horizontal control for the photogrammetric processing of the photographs, as well as providing control for the 3D model obtained from the laser scan data.

Other sources of information were the National Museums of Kenya, the National Archives of Kenya, the Internet, and the literature listed in the reference section, amongst others.

## 5.3 Overview of 3D Modelling

There are three main categories of 3D models; namely, the wire frame model, the surface model, and the solid model (Hanke & Grussenmeyer (2002) and Mngumi & Ruther (2004)). Figure 5.3 shows the various categories of the 3D models.

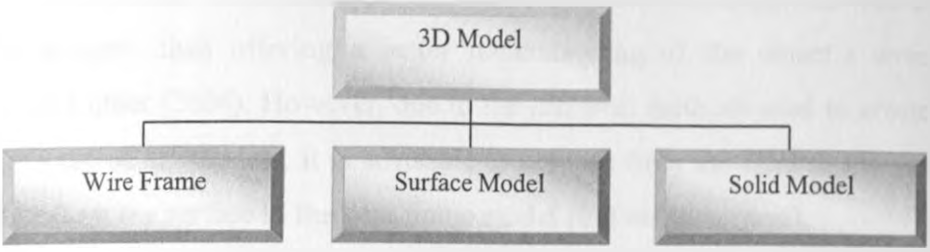



*Figure 5.3: Overview of 3D Models (Hanke & Grussenmeyer, 2002)*

A wire frame model is a skeletal description of a 3D object, which consists of points, lines, and curves that define its outline. This type of modelling can be very time-consuming because each object that makes up a wire frame model must be independently drawn and positioned. It is the basic form of presentation, and is suitable for simple objects. Figure 5.4 shows a wire frame (line) model of a section of the Old PC's Office building as modelled from the laser scan data (see section 5.5.3 for details on the modelling).

Surface modelling not only defines an object's outline, but also the surfaces in between the edges. A surface model consists of individual planes forming a faceted, polygonal mesh, thus making it more sophisticated than the wire frame model. Figure 5.5 shows the surface model from which the line model in Figure 5.4 was drawn (see section 5.5.3 for details on the modelling).

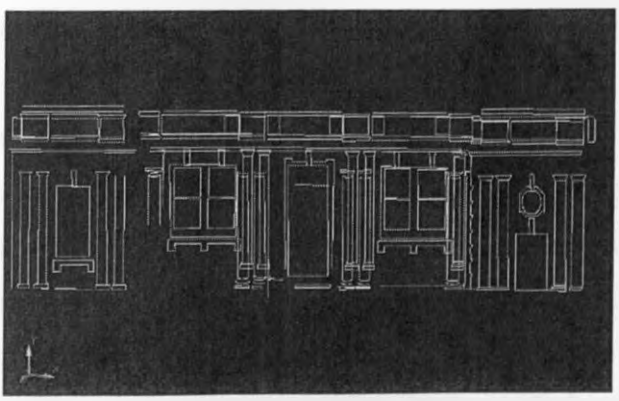


*Figure 5.4: Wire frame Model of the Old PC's Office Building.*

The solid (volume) model is the highest form of representation in the modelling hierarchy. It provides information about the boundaries of the object as well as its enclosed volume, thus offering a better understanding of the object's structure Mngumi & Ruther (2004). However, due to the different methods used to create the different types of 3D models, it is advisable to convert from the solid to the surface model and from the surface to the wire frame model (but not vice versa).

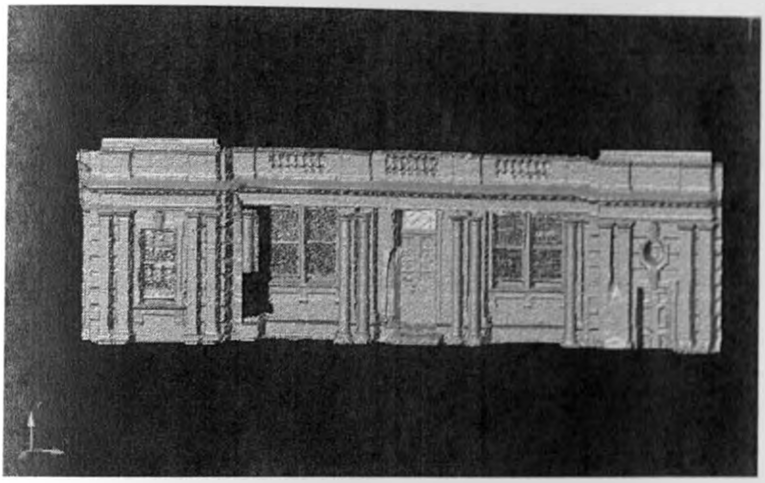


*Figure 5.5: Surface Model of the Old PC's Office Building.*

## 5.4 3D Modelling from Close Range Imagery

### 5.4.1 Image Acquisition

**Provision of Photo Control**

The establishment of photo control for the study area was not trivial since most geodetic control points in the Nairobi CBD no longer exist on the ground. The control points were either destroyed during re-carpeting of roads, or in the expansion of buildings, etc. Most of the cadastral plans only show theoretical control points, an indication that the surveyor failed to recover the old control points during the survey. Therefore, the control points along the private *Railway Club* provided the much-needed control to run the traverse using a T2 theodolite, together with a Wild

DI3000S EDM (Electromagnetic Distance Measurement). The accuracy of the traverse is given in Appendix A.

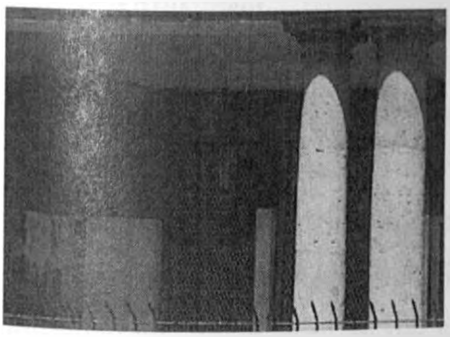
The final coordinates of the control points are in the Cassini Soldner Coordinate System since the available cadastral plans are still referenced with respect to the Cassini Soldner projection.

**Photography of the Monument**

The photographs (20 in number) for the old PC's office building were procured using a digital camera (*Kodak DCS 330)* with a 14mm – 28mm lens, with adjacent photographs having a sufficient amount of overlap. The back section of the building facing *Nyayo House* was obscured by an iron sheet fence, and was therefore not photographed.

### 5.4.2 Image Processing

The images of the old PC's office building needed digital image enhancement to improve their visual interpretability. Figure 5.6 shows a section of an image enhanced using PhotoModeler in which the outline of the window and the column are not clearly definable. Like most CRP software, PhotoModeler has a module for simple image enhancement, which is useful in such instances of sun-shadowed façades.



*(a)*

*(b)*

*Figure 5.6: Digital Image Enhancement. (a) Image with sun-shadowed facades. (b) Same image digitally enhanced to increase the brightness of the imaged façade.*

### 5.4.3 Photogrammetric Solution

The software used for solving the fundamental photogrammetric problem was PhotoModeler 4.0 (Eos System Inc). Generally, the basic steps involved in creating a 3D model using this software include: provision of the calibration parameters of the cameras or an approximate description of the camera (where the camera calibration parameters are unknown); marking features on the photographs; image matching; bundle adjustment; and lastly (where necessary), exporting the resulting 3D model to a CAD or animation software for further processing.

**Camera Description**

PhotoModeler has been designed (as is the case with majority of the CRP software) to accommodate photographs from metric, semi-metric, or non-metric cameras, whether these are calibrated or not. If the camera is not calibrated (or if the calibration parameters are suspect), the software has algorithms that allow an on-the-job self-calibration of the camera to take place during the photogrammetric processing. In order to use the self-calibration option during the processing stage, basic information about the camera used for the photography of the monument was input into the software. This information included the focal length (28mm), the image format (*2008 X 1504*), and sensor type (i.e. *Kodak DCS 330*).

**Bundle Adjustment**

In order to model the selected section of the building, four photographs were identified and loaded into the software, alongside the camera description. In the next step, the first pair of overlapping photographs (say 1-2) was selected and 6 tie points were marked on each photograph. These points were specifically chosen to fulfil the following conditions: they all did not lie on the same plane and that they uniformly covered the overlap areas between the photographs. These points were matched; this is basically a process of telling the software that a marked point on two or more photographs represents the same object point. This was repeated for the next pair of overlapping photographs (i.e. 2-3); with the additional requirement that at least 2 of the tie points should also appear on photo 1. And lastly, the same was repeated for photos (3-4), with at least 2 of the tie points appearing in photo 2.

Thereafter, the measured photo coordinates of all the tie points, together with the basic camera data were simultaneously processed together to estimate the camera calibration parameters (interior orientation elements), the exterior orientation elements (i.e. the position and orientation in space of the various camera stations), and the 3D coordinates. This processing is iterative, and is normally referred to as the bundle adjustment method, where a simultaneous solution incorporates the inner and outer orientation parameters of the camera stations, and the object space coordinates of object points, all as unknowns Karara *et al* (1980) (see Appendix C).

The results of the bundle adjustment have been tabulated for ease of explanation. Table 5.1 gives resolved exterior orientation parameters, whereas the results of the camera calibration parameters of the camera used in the study can be found in Table 5.2. Since it is possible to use different cameras for the same project, the software does not assume that all the photographs were acquired using the same photograph. This is quite advantageous since it allows more flexibility during image acquisition, where more than one camera can be used to quickly obtain the necessary imagery. The calibration results give the focal length of the camera; the size of the imaging format of the camera (in terms of width and height); the coordinates of the camera principal point; the radial lens distortion parameters (i.e. K1 and K2) and the tangential lens distortion parameters (i.e. P1 and P2); the largest marking residual on each photograph; and lastly, the RMS (root mean square) marking residual on each photograph. In Table 5.1, the coordinates of each camera station is defined by the center XYZ coordinate, with omega, phi and kappa denoting the rotation angles that define its orientation in space about the X, Y, Z axis respectively.

In Table 5.2, the large RMS value of 41.62 pixels is an indication that photograph number 1 did not orient well. This is also reflected in the value of its largest marking residual of 109.87 pixels, which is the highest amongst all the four photographs. A close look at the configuration of the four camera stations used in the bundle adjustment (see Figure 5.7) can be used to explain this unsatisfactory results. This shows that adjacent camera stations are very close to and are almost parallel to each other. This weakens the geometry of the rays that intersect to define a point in space. Furthermore, this type of configuration can introduce instability in the normal equation matrix formed during the bundle adjustment. In an ideal situation, the rays (from different photographs) that intersect to define a point in space should have good intersection angles (as close to 90° as possible).

| Photo Number | Description | Oriented | Center X (m) | Center Y (m) | Center Z (m) | Omega (deg.) | Phi (deg.) | Kappa (deg.) |
|---|---|---|---|---|---|---|---|---|
| 1 | pc2 | Yes | 1.550472 | -15.0861 | 0.629771 | 87.2876 | 12.170097 | 4.772687 |
| 2 | pc3 | Yes | 1.237247 | -15.1975 | 0.448695 | 87.8385 | 21.048716 | 2.404034 |
| 3 | pc4 | Yes | -19.0135 | -8.609805 | -1.040052 | 91.7824 | -42.8887 | 8.326618 |
| 4 | pc5 | Yes | -20.3302 | -7.947179 | -1.193336 | 97.5612 | -57.3796 | 14.483795 |

*Table 5.1: PhotoModeler's Exterior Orientation Results.*

| Photo Number | Camera | Focal Length (mm) | Format Width (mm) | Format Height (mm) |
|---|---|---|---|---|
| 1 | Edit Parameter | 28.647713 | 18.072000 | 13.536000 |
| 2 | Edit Parameter | 28.475720 | 18.072000 | 13.536000 |
| 3 | Edit Parameter | 28.612894 | 18.072000 | 13.536000 |
| 4 | Edit Parameter | 28.380382 | 18.072000 | 13.536000 |
| | | | | |
| **Photo Number** | **Principal Point X (mm)** | **Principal Point Y (mm)** | **K1** | **K2** |
| 1 | 9.036000 | 6.768000 | 0.000182 | -0.000001 |
| 2 | 9.036000 | 6.768000 | -0.000352 | 0.000003 |
| 3 | 9.036000 | 6.768000 | 0.000767 | -0.000005 |
| 4 | 9.036000 | 6.768000 | 0.000689 | -0.000016 |
| | | | | |
| **Photo Number** | **P1** | **P2** | **Largest Residual (pixels)** | **RMS Residual (pixels)** |
| 1 | 0.003603 | -0.000140 | 109.8655 | 41.621300 |
| 2 | -0.002220 | -0.000031 | 57.99427 | 6.902754 |
| 3 | -0.001239 | -0.000456 | 5.706437 | 1.721024 |
| 4 | 0.004771 | -0.000793 | 33.565423 | 6.990545 |

*Table 5.2: Camera Self-Calibration Results from PhotoModeler.*

*Figure 5.7: Configuration of the Camera Stations.*

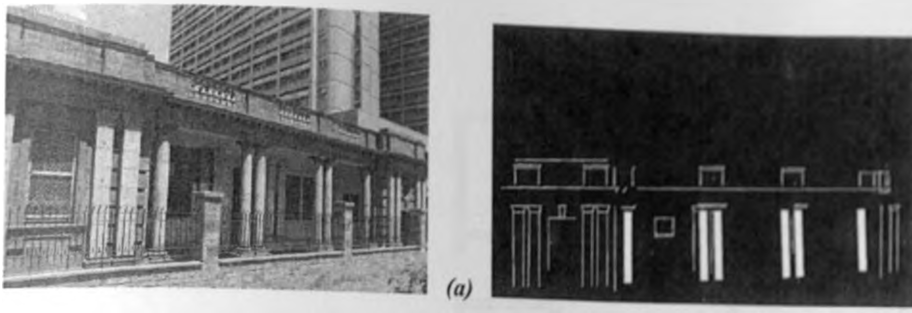
### 5.4.4 3D Modelling

**Wire Frame Modelling**

3D object modelling in CRP mainly involves creating a wire-frame (line model) and thereafter draping the resultant 3D model frame with texture from the photographs. The level of detail to be modelled should be commensurate with the use of the model.

The final result of the bundle adjustment is the estimation of the 3D coordinates of object points marked in the photographs, which define object's features of interest. The wire frame modelling was a purely manual task, and hence very time consuming as it involved visual interpretation and manual measurements. Figures 5.8 (b) shows the line model of features that could be modelled accurately. One of the challenges encountered during this modelling phase was that for most of the points, the software could not compute their 3D coordinates since the rays from adjacent photographs were intersecting at very low angles as discussed in section 5.4.3. Clearly, most of the modelled features are those that were appearing on those photographs that formed a good geometry.

Despite this, it is clear that photogrammetry has a lot of potential in modelling buildings for purposes of conservation. Nevertheless, there is an imperative need to complement photogrammetry with another mapping technique such as laser scanning in order to effectively model complex buildings comprehensively.



(a) (b)

*Figure 5.8: 3D Modelling using Photogrammetry. (a) Image of a section of the PC's Office Building. (b) Line model of selected features imaged in (a).*

# 5.5 3D Modelling using Laser Scan Data

## 5.5.1 Point Cloud Data Acquisition

*Cyrax 2500* laser scanner was used to scan the Old PC's office building (see Appendix D on specifications of the laser scanner). A total of 16 laser scans were taken, covering the main entrance, and the sides facing *Uhuru Highway* and *Kenyatta Avenue*. The approximate positions of the laser scanner during the data capture are shown in Figure 5.9.

Just like for the photography, the section of the building facing *Nyayo House* was omitted due to the presence of a temporary (iron sheet) fence that was too close to the building for the scanning to be effective. The scanning was done at 20mm by 20mm resolution, with a sub scan of 5mm by 5mm. Figure 5.10(a) shows a photograph of a section of the building, as taken by the digital camera on the laser scanner. Figure 5.10(b) shows the corresponding laser scan, which comprises a collection of closely spaced dots where each dot is coordinated in 3D.

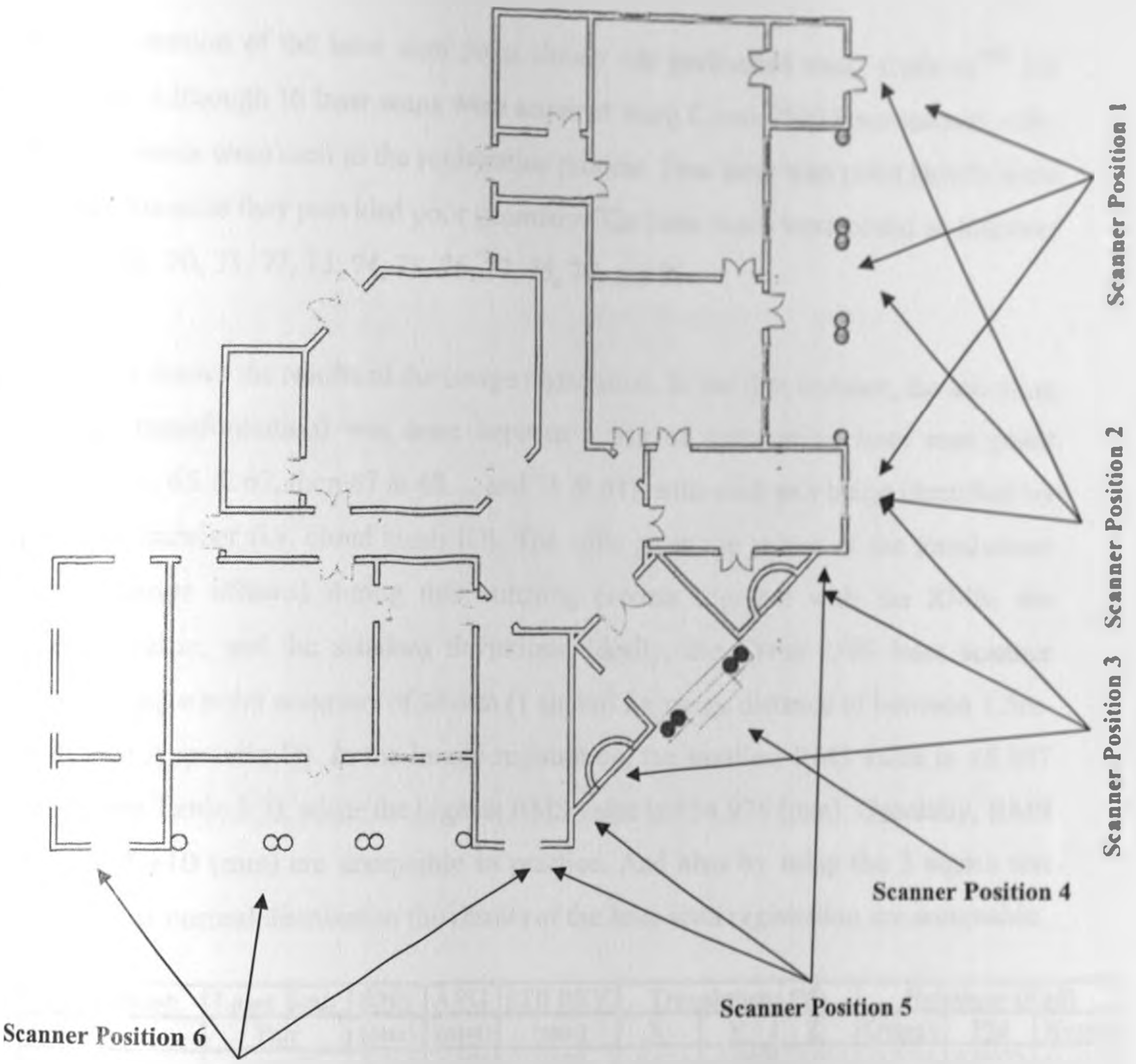



*Figure 5.9: Configuration of the Laser Scanner Positions Employed in the Study (Source: NMK Planning & Exhibits Dept).*

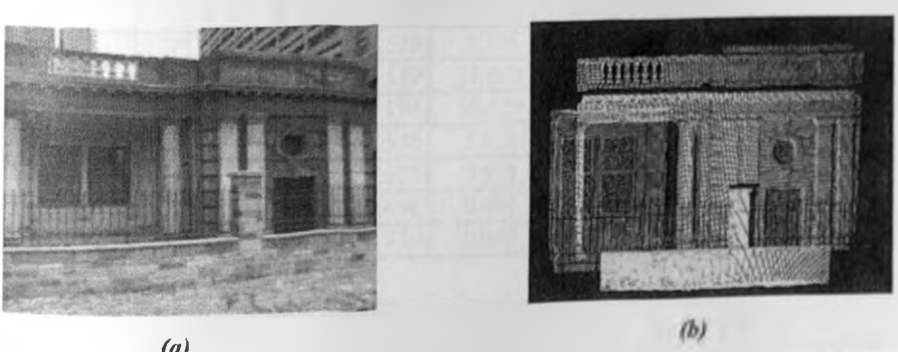



*Figure 5.10: Laser Scan Point Cloud Data. (a) Image captured using a scanner. (b) Corresponding laser scan 3D point cloud.*

### 5.5.2 Image Registration

The registration of the laser scan point clouds was performed using Cyclone™ 3.0 software. Although 16 laser scans were acquired using *Cyrax 2500* laser scanner, only 14 laser scans were used in the registration process. Two laser scan point clouds were omitted because they provided poor geometry. The laser scans were coded as follows: 65, 67, 68, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, and 81.

Table 5.3 shows the results of the image registration. In the first instance, the stitching (i.e. the transformation) was done between a pair of overlapping laser scan point clouds (i.e. 65 & 67, then 67 & 68… and 78 & 81), with each pair being identified by a unique number (i.e. cloud mesh ID). The table gives the values of the translations and rotations effected during this stitching process together with the RMS, the average value, and the standard deviations. Ideally, the *Cyrax 2500* laser scanner gives a single point accuracy of ±6mm (1 sigma) for range distance of between 1.5m-50m (see Appendix D). In the image registration, the smallest RMS value is ±5.897 (mm) (see Table 5.3), while the highest RMS value is ±14.978 (mm). Generally, RMS values of ±10 (mm) are acceptable in practice. And also by using the 3 sigma test standard of normal distribution the results of the laser scan registration are acceptable.

| Cloud/Mesh | Laser Scan | RMS | AVG | STD DEV | Translations (M) | | | Rotations (Rad) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | Pair | (mm) | (mm) | (mm) | X | Y | Z | Omega | Phi | Kappa |
| 1 | 65 & 67 | 8.045 | 4.498 | 6.670 | -0.034 | -0.002 | -0.019 | -0.0708 | 0.9972 | -0.0237 |
| 2 | 67 & 68 | 6.600 | 4.012 | 5.240 | -0.031 | -0.001 | -0.019 | 0.0030 | 0.9999 | -0.0098 |
| 3 | 68 & 70 | 9.101 | 5.445 | 7.291 | -5.079 | 0.054 | -3.525 | -0.0254 | -0.9988 | -0.0428 |
| 4 | 70 & 71 | 6.550 | 3.957 | 5.220 | -0.028 | 0.003 | -0.014 | 0.0716 | 0.9974 | -0.0087 |
| 5 | 71 & 72 | 14.978 | 7.560 | 12.930 | -9.796 | -0.364 | -5.779 | -0.0352 | -0.9966 | 0.0739 |
| 6 | 72 & 73 | 5.897 | 4.277 | 4.059 | -0.045 | 0.000 | -0.018 | 0.0019 | 0.9977 | 0.0673 |
| 7 | 73 & 74 | 9.554 | 5.523 | 7.795 | -5.731 | 0.410 | -4.209 | 0.1675 | -0.9858 | -0.0130 |
| 8 | 73 & 75 | 13.898 | 7.559 | 11.662 | -11.616 | 0.902 | -9.932 | 0.0698 | -0.9974 | -0.0197 |
| 9 | 73 & 76 | 13.580 | 8.194 | 10.829 | -11.616 | 0.904 | -9.862 | -0.0036 | -1.0000 | -0.0080 |
| 10 | 75 & 77 | 7.087 | 4.545 | 5.438 | -14.524 | 0.146 | -1.696 | -0.1591 | -0.9872 | -0.0067 |
| 11 | 77 & 79 | 7.237 | 4.675 | 5.525 | -4.073 | -0.036 | 1.265 | -0.1389 | 0.9878 | -0.0701 |
| 12 | 78 & 79 | 7.093 | 4.496 | 5.486 | -4.180 | 0.114 | -0.682 | -0.0713 | -0.9788 | -0.1918 |
| 13 | 78 & 81 | 12.049 | 6.770 | 9.967 | -16.955 | 0.677 | -11.744 | 0.0108 | -0.9968 | -0.0791 |

***Table 5.3: Laser Scan Registration Results.***

Thereafter, all the different laser scan pairs were then transformed (i.e. registered) into a uniform coordinate system that was chosen from one of the laser scan point clouds *à* *priori* (i.e. scan 65 in this case). This procedure is akin to the concept of block triangulation in photogrammetry where all the different models are transformed into a uniform coordinate system defined by one of the models.

Figure 5.11 (a) and Figure 5.11 (b) show the registered 3D model of the Old PC's office building as viewed from the top and the front, respectively.

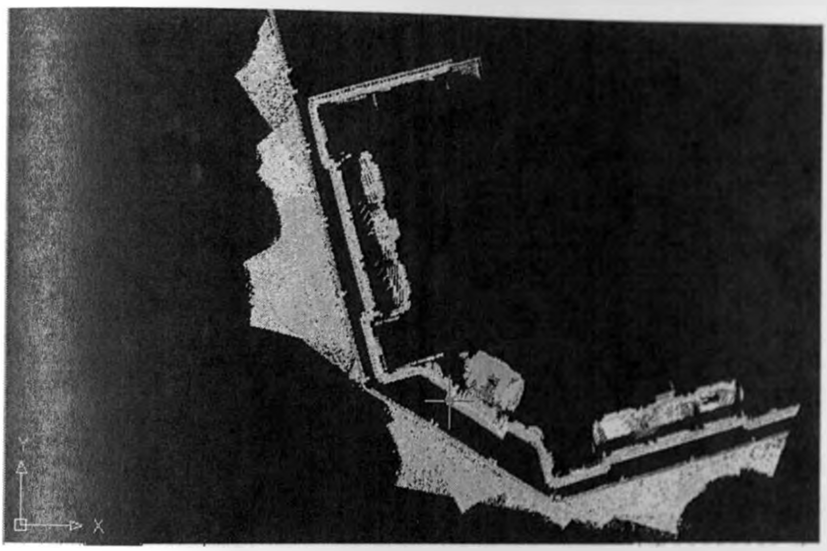



***Figure 5.11(a): Plan View of the Registered Laser Scan.***

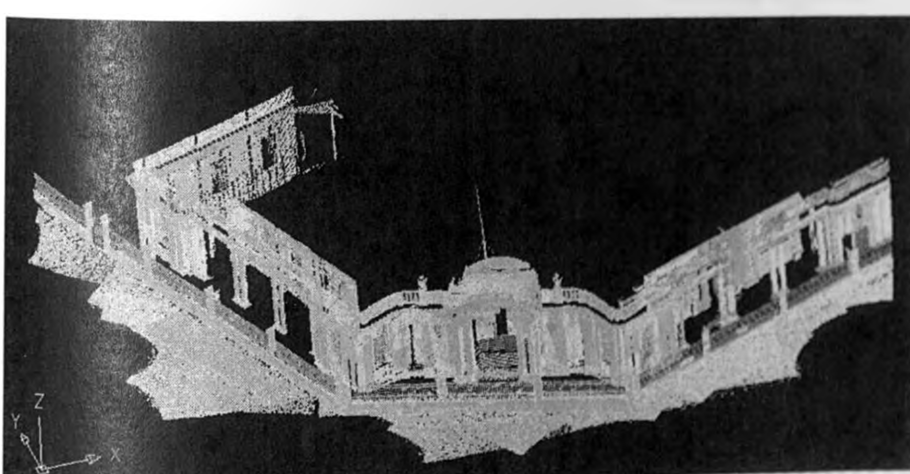



***Figure 5.11(b): Front View of the Registered Laser Scan.***

### 5.5.3 3D Modelling

**Surface Modelling**

Figure 5.12 gives a summary of the processes involved in the 3D modelling (i.e. the surface and line model) of the laser scan data. AutoCAD 2002 and Golden Surfer 7.0 are the key software used for modelling, as these are more easily available and affordable as compared to the Cylone™ 3.0. Cyclone™ 3.0 and the accompanying laser scanner are sold as a single unit, making it very expensive.

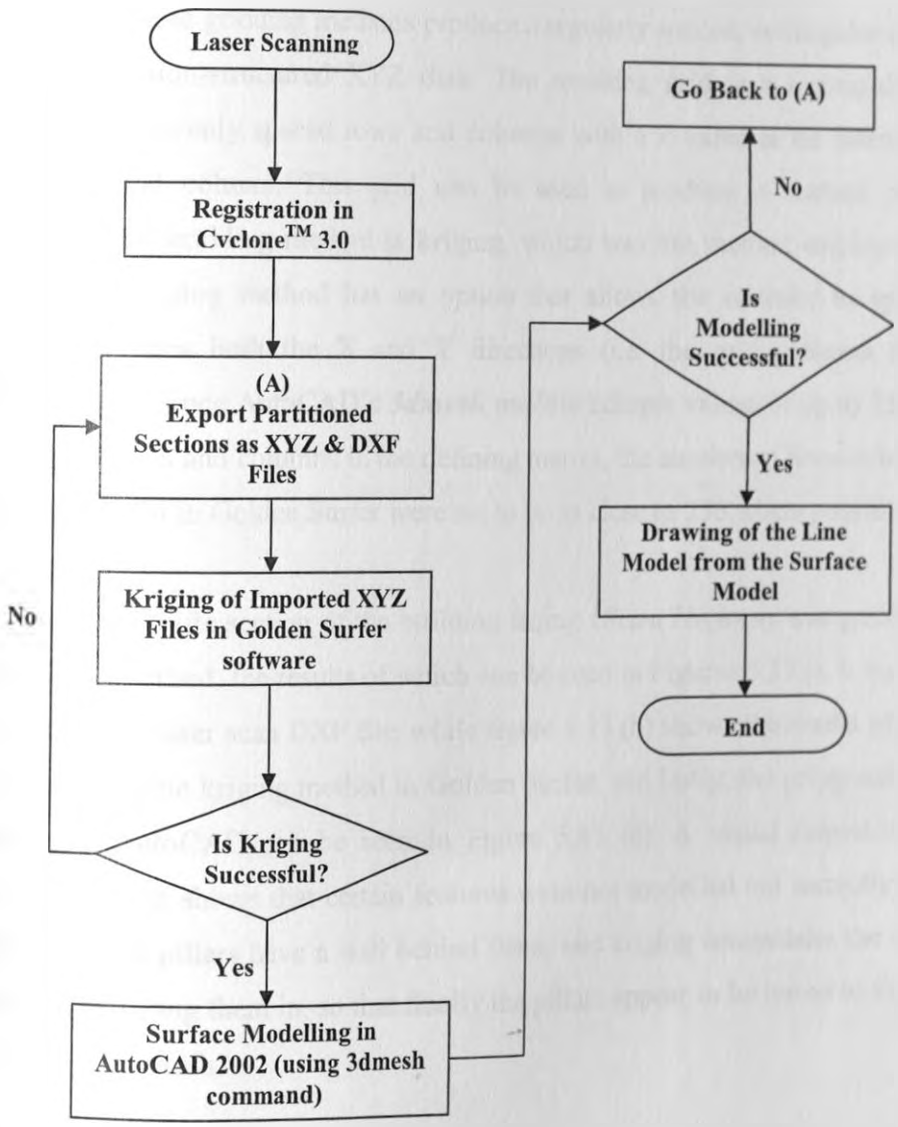



*Figure 5.12: Laser Scan 3D Modelling Flow Chart*

Cyclone™ 3.0 can export point cloud data in a number of formats including the DXF and the XYZ formats, which can be imported into many CAD software for further processing. AutoCAD has various algorithms for creating polygonal meshes in either 2D or 3D. ***3dmesh*** is one such module that can be used to create a free-form polygonal mesh defined by an M by N size matrix; where M and N represent the number of rows and columns respectively. The input file for this module should be in the form of a structured XYZ data file. However, the XYZ data exported from Cyclone™ 3.0 is not stored in a structured manner.

The Golden Surfer 7.0 provides a means of structuring the data through the gridding command. These gridding methods produce a regularly spaced, rectangular array of Z values from non-structured XYZ data. The resulting grid is a rectangular region comprised of evenly spaced rows and columns with a Z value at the intersection of each row and column. This grid can be used to produce a contour map. The recommended gridding method is kriging, which was the method employed in this study. The kriging method has an option that allows the operator to specify the number of lines both the X and Y directions (i.e. the grid columns and rows respectively). Since AutoCAD's ***3dmesh*** module accepts values of up to 256 for the number of rows and columns in the defining matrix, the number of lines in both the X and Y direction in Golden Surfer were set to be as close to 256 where possible.

Initially, the whole section of the building facing *Uhuru Highway* was gridded using the kriging method, the results of which can be seen in Figures 5.13 (a, b &c). Figure 5.13 (a) is the laser scan DXF file, while figure 5.13 (b) shows the results of gridding process using the kriging method in Golden Surfer, and lastly, the polygonal mesh as created in AutoCAD can be seen in Figure 5.13 (c). A visual inspection of the polygonal mesh shows that certain features were not modelled out correctly (e.g. the pillars). These pillars have a wall behind them, and kriging interpolates the spaces in between by filling them in, so that finally the pillars appear to be joined to the wall in the polygonal mesh.

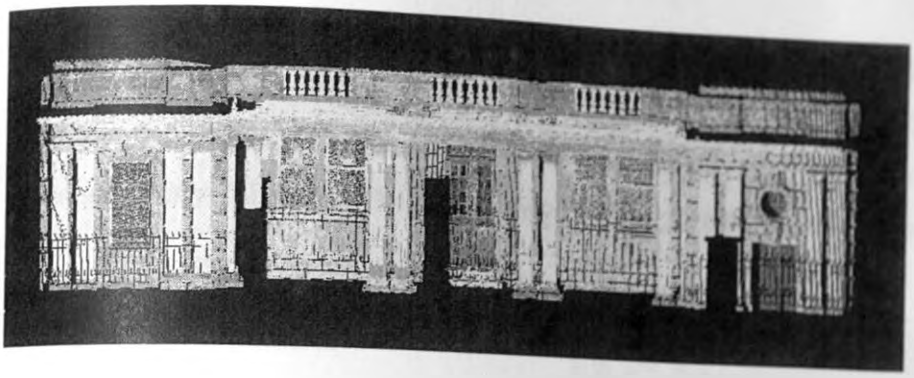


*Figure 5.13 (a): Laser Scan of the Section facing Uhuru Highway.*

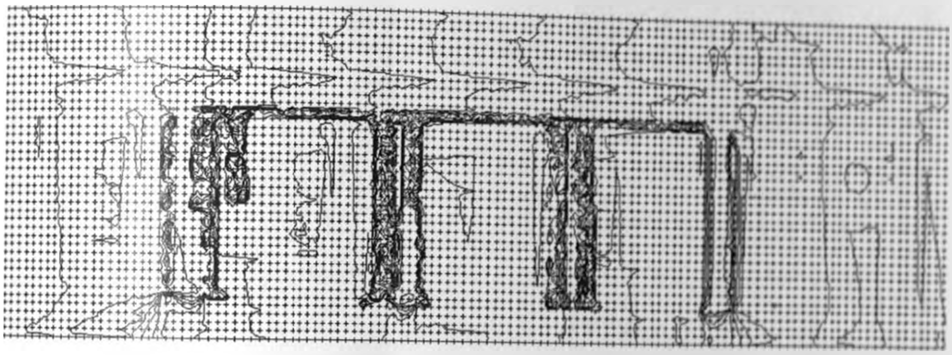


*Figure 5.13(b): Grid File resulting from Gridding using Kriging Method.*

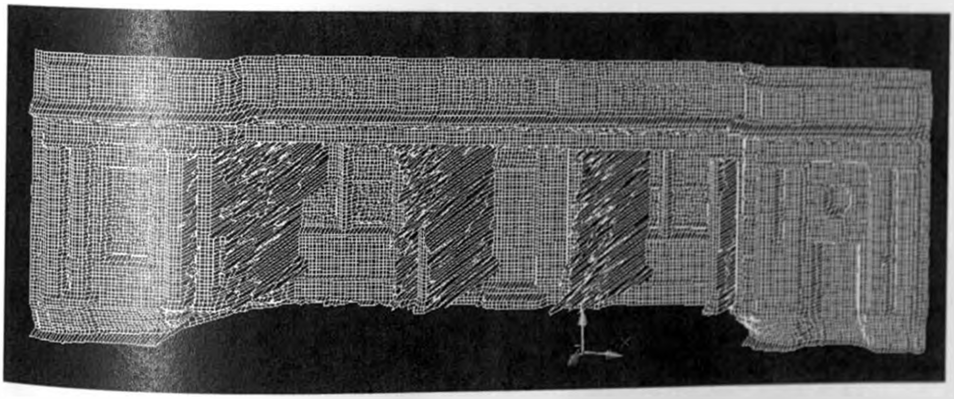
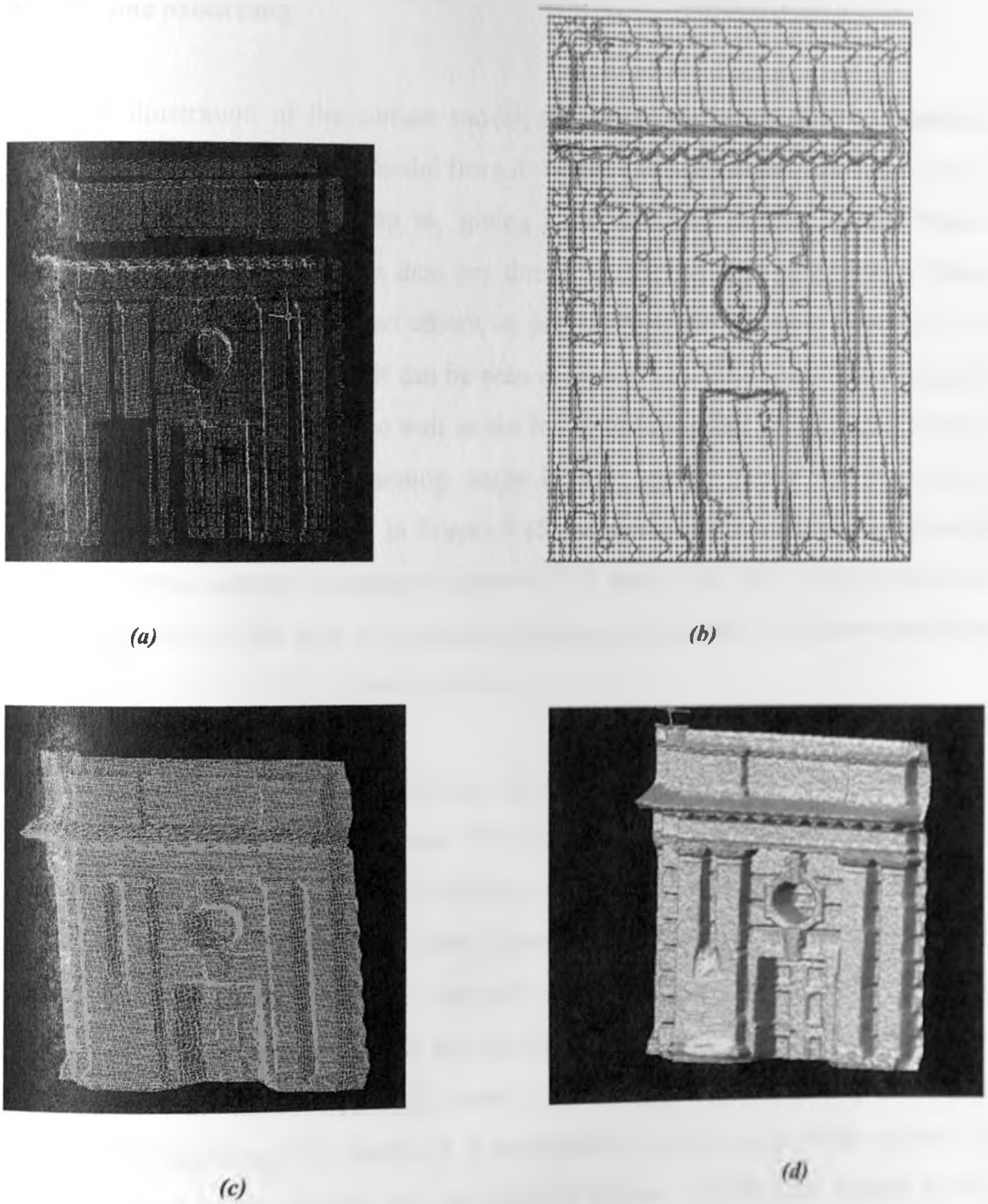


*Figure 5.13(c): The Polygonal Mesh created in AutoCAD from Figure 5.12(b).*

In order to avoid this type of interpolation, this section was partitioned into five planar segments, so that all the features in each segment lie in (approximately) one plane. Each of these was gridded using the kriging method to create the grid files. These grid files were then converted into a 'comma separated variable' (.csv) files, which can be viewed in a text editor such as WordPad. The data in these files is what was used as input in AutoCAD's ***3dmesh*** module to create the polygonal mesh. Figure 5.14 illustrates the surface reconstruction of one of the segments. The edges in the building are more clearly definable in the surface model, making it easy to draw the wire frame from it.



*(a)* *(b)* *(c)* *(d)*

***Figure 5.14: Laser Scan Surface Modelling. (a) Original Laser Scan. (b) Contour Map in Golden Surfer 7.0. (c) 3D Mesh in AutoCAD 2002. (d) The 3D Mesh rendered in AutoCAD 2002.***

Since each of these segments share one common coordinate system, they were tied together to create a continuous surface model of the entire section of the building facing *Uhuru Highway*, as can be seen in Figure 5.5 (draped with artificial computer generated texture).

**Wire Frame Modelling**

From the illustration of the surface model, the edges are more clearly definable, making it easy to draw the line model from it. Where there are gaps in the laser cloud, the kriging procedure fills them in, giving it an artificial surface texture. These discontinuities in the laser scan data are due to occlusions that occur either when certain features are hidden behind others, or as a result of the scanning direction. For the first instance, a good example can be seen in Figure 5.14. The fence that surrounds the building occluded part of the wall in the lower section gives an unnatural texture in the surface model. The scanning angle is also another factor that introduces discontinuity in the laser cloud. In Figure 5.15, the arrow in white shows the general direction of the scanner during data capture. It is clear from this figure that when scanning face-front, the wall on the left side was also occluded. The laser scan data can be recaptured for such occluded sections.

Given the complexity of this building, producing a high quality line drawing is extremely demanding. It is not trivial. The plot quality of line models is not always consistent, and some forms of architecture (e.g. rounded features) do not plot well Cooper & Robinson (1996). In addition, representation of badly eroded or sculptural features is often unsatisfactory. One can only draw what is there bearing in mind that rounded edges do not draw out well. For buildings with a high level of surface details, a surface model would be applicable since it follows closely the undulations on the surface of the building. This capability is very useful in determining which sections of a building are badly eroded, and in need of urgent repairs (see Figure 5.16). Geometric measurements of the deformations can be obtained directly from the model, without any form of physical contact.

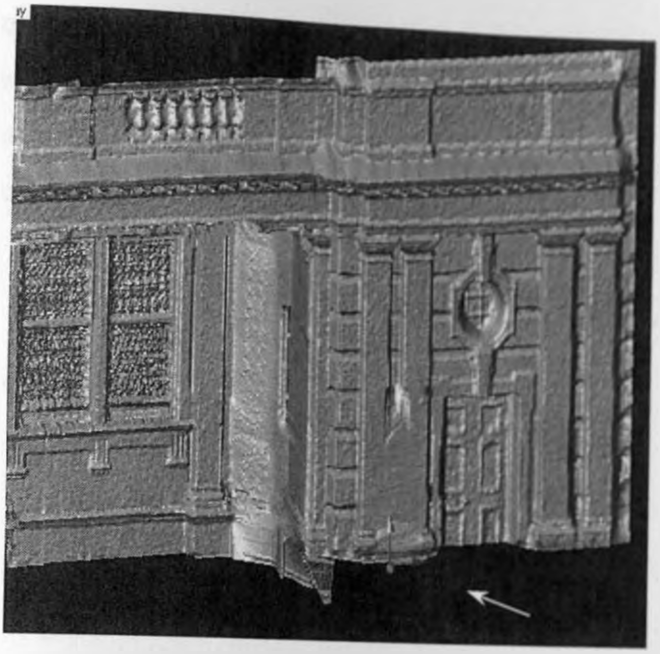
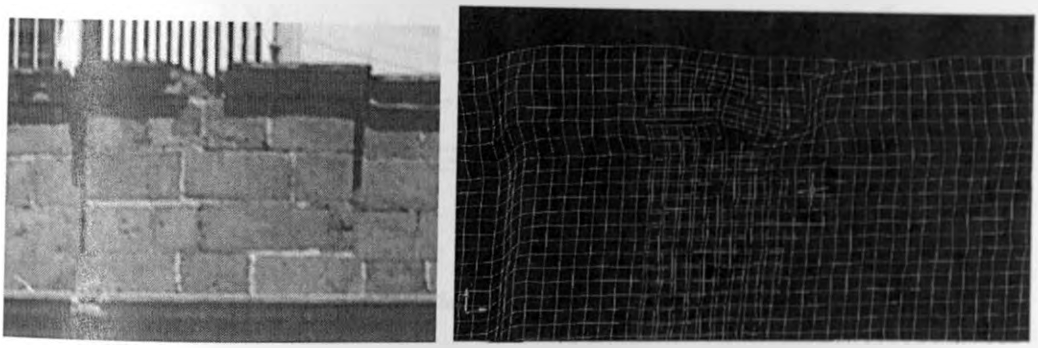


*Figure 5.15: Smoothing-over Effect of Gridding in Surfer.*



*(a)* *(b)*

***Figure 5.16: Representation of a Badly Eroded Feature. (a) Photograph showing the eroded section. (b) Surface model representation of the eroded part.***

Finally, Figure 5.17 shows the 2D plan of the monument, drawn from both the laser scan data in Figure 5.11 (a) and from field measurements obtained from taping the building. See Appendix H for the enlarged 2D Plan. This plan is comparable to the floor plan obtained from the National Museums of Kenya (Figure 5.8). Figure 5.17 displays the lengths of those segments as obtained from both methods. The highest difference is 0.14m, and the lowest difference is 0.03m (see Appendix E for a comparison between laser scanning and tape measurements).

In addition, the height of the building as obtained from the traverse is 5.0m (see Appendix B), whereas the height of the building as measured from the laser scan is also 5.0m. This is a good indicator that the measurements obtained from the laser scanning are comparable to those obtained by the traverse survey.

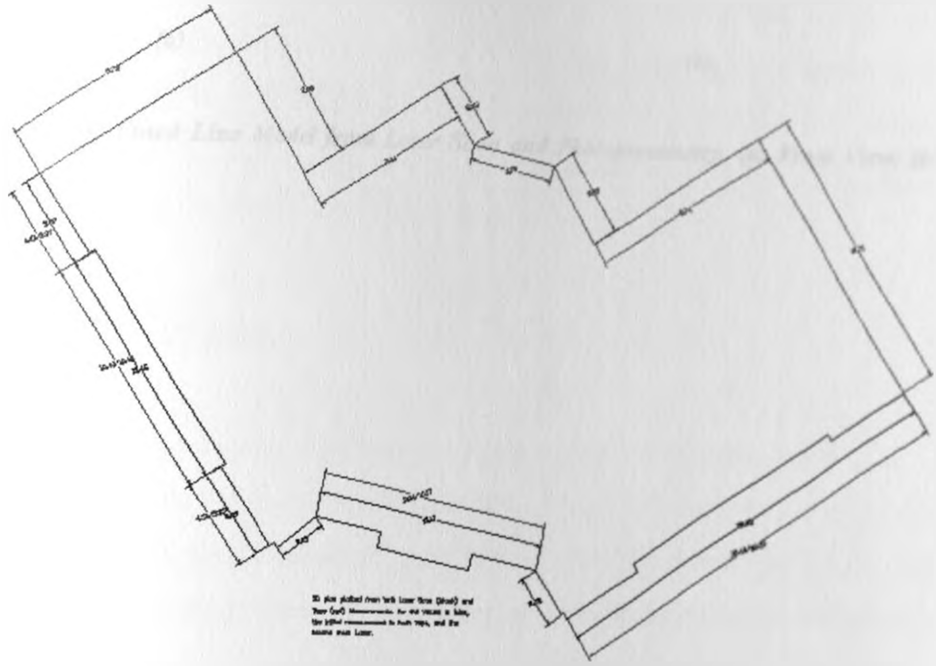
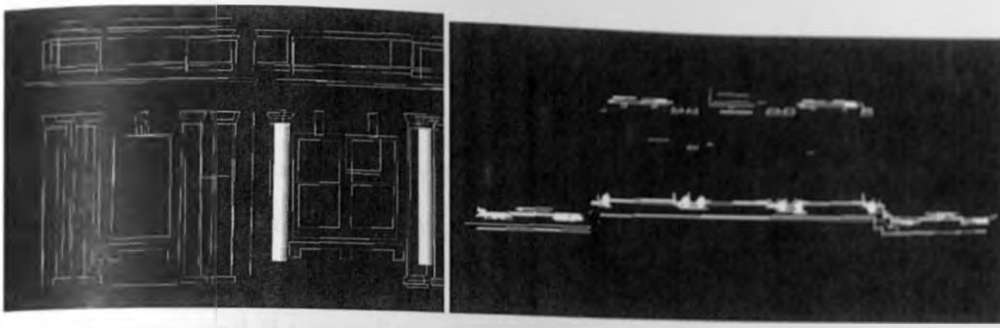


*Figure 5.17: 2D Plan of the Old PC's Office Building.*

## 5.6 Data Fusion

The data fusion of the line model from laser scan with the line model from photogrammetry is not satisfactory as can be seen in Figure 5.18. The data fusion was done using AutoCAD software. Figure 5.18(a) shows that the two models are not properly aligned. As earlier explained in section 5.4.3, adjacent camera stations were very close to each, a situation which could have introduced instability in the normal equation matrix formed during the bundle adjustment. It is possible that the 3D model from photogrammetry is suspect, therefore resulting in a fused model that is not correctly aligned. Despite this shortcoming, the results provide an indication that it is possible to combine the two technologies to produce a more comprehensive model.



*(a)* *(b)*

***Figure 5.18: Fused Line Model from Laser Scan and Photogrammetry. (a) Front View. (b) Plan view.***

# 6. CONCLUSIONS AND RECOMMENDATION

The main objective of this study was to introduce the concept of employing 3D visualization in the documentation of cultural sites and monuments in Kenya, using modern mapping techniques. This visualization is in the form of 3D models (i.e. the surface model, and the wire-frame model). Close range photogrammetry and laser scan technology are the techniques used to map the building in 3D, with a traverse survey providing control for the 3D modelling. The main emphasis is on 3D surface and wire-frame modelling from laser scan data using an alternative methodology, in the absence of software specifically designed to process point cloud data.

## 6.1 Conclusions

There is an urgent need to preserve a society's cultural heritage for future generations, and also to safeguard them against destruction from natural and man-made threats. Therefore, the documentation of such sites should be as comprehensive and as detailed as possible to ensure that in case of any eventuality, the monument can be re-built to its original form as closely as possible. Such detailed, accurate geometric data is best captured using modern digital mapping technologies, such as close range photogrammetry and laser scan technology. With these technologies, large volumes of data can be captured with ease; processed and presented in suitable formats. In addition, the captured geospatial data is also easily integrated into a GIS. This study confined itself to the 3D mapping and modelling of the old PC's office building using both close range photogrammetry and laser scan technology.

From the laser scan data, a 3D point cloud model of the building (except for the rear part which was obscured by a temporary iron sheet fence) was reconstructed using Cyclone™ 3.0 software. However, it was not possible to create an acceptable surface model using the same software since the generated surface model appeared very jagged. The plausible reason for this is that Cyclone™ 3.0 software was initially designed for use in industrial plants. It has a module for creating surface models from point cloud data. This module has algorithms for fitting geometric primitives to create features such planes, cylinders, cones, and spheres, which are commonly found in industrial plants. When it comes to cultural heritage documentation, these monuments often consist of complex architectural designs with complicated building facades (such as those found on the old PC's office building) that are not easily reduced to such simple forms of representation. As a result, the above primitives are not usually adequate for the proper representation of the objects encountered in cultural heritage documentation.

It is for this reason that it became necessary to use an alternative methodology to create the surface model, and thereafter the line model of the section of the building facing *Uhuru Highway*. The proposed methodology is more cost-effective since it makes use of AutoCAD (AutoCAD 2002 costs approximately USD 3,395) and Golden Surfer software (Golden Surfer 8.0 costs approximately USD 599), which are cheaper software compared to the Cyclone™ 3.0 software (which when sold together with the scanner ranges between USD 20,000 to USD 40,000). However, it is important to note that the proposed method is tedious and time consuming, since AutoCAD was not designed to neither handle nor process large point cloud data.

For the proposed method to be effective, the modelling should be done on a piece-meal basis, which is also what most literature advocate as the best way forward in the 3D modelling for the purpose of documentation. In some instances, detailed analysis of the monument would be more suitably done directly on the unregistered laser scan data. The results obtained using the prescribed methodology shows that it is viable, but more caution has to be exercised in the data capture to ensure that the important features are not occluded. Given the complexity of the old PC's building, modelling of building with simple façades using this methodology would most likely be much easier, and the results more acceptable.

On the other hand, the 3D modelling in photogrammetry was not satisfactory due to the relatively weak configuration of the camera stations during the data capture. When modelling using PhotoModeler, the largest residual should not be more than 10 pixels. However, Table 5.2 indicates that only one photograph (out of four) has the largest residual being less than the recommended 10 pixels (its largest residual is recorded as

5.71 pixels). This photograph (number 3) also has the least RMS value of 1.72 pixels. Very large residual values are an indicator that either the camera calibration parameters are in error, or one (or more) computed camera station position and orientation is in error. As explained in section 5.4.3, the weak configuration of the camera stations may have contributed to these large residual errors in the 3D model. These errors may also have contributed to imperfect alignment (or fusion) of the line model from photogrammetry with the line model from laser scanning.

Nevertheless, even though the fused model does not overlay perfectly, the results show that there is more to be gained by integrating the two technologies. In the integrated methodology proposed, the laser scans would provide 3D surface information, while the 3D model from close range photogrammetry would provide geometric detail of the object. Hence, the two technologies would complement each other.

A strong point in laser scanning is that the point cloud data acquired in the field is already coordinated in 3D, whereas with photogrammetry, measurements are done on the photographs to generate points that are later coordinated in 3D. The amount of points generated with a laser scanner for a single scan can total to a hundred thousand, which enables it to map the surface of an object more accurately, including sections that may be eroded. If the surface model generated is likened to a DTM, then the amount of structural deformation (or erosion) on an object can be quantified in quasi real time. Photogrammetry is also capable of providing this information, but it is a much more involving process, when compared with the laser scanning. For this reason, laser scan has a major role to play in the preservation and restoration of cultural sites and monuments.

## 6.2 Recommendations

The advantages of incorporating 3D visualization in documenting heritage sites are well documented in literature. The National Museums of Kenya should make use of these modern technologies for the mapping and documentation of cultural sites and monuments. However, documentation should not be seen as an end by itself, but should be considered as being part of a wider concept, such as a Cultural Heritage Information System (CHIS). As a decision support tool, the CHIS would consist of a database integrating all the various cultural sites and monuments distributed across the country. The CHIS should be structured such that it not only provides access to information related to cultural heritage, but it also provides a means for the users to evaluate the usefulness of the data for their own applications. There should also be some form of visualization of the data, which would be a direct application of the 3D models incorporated as part of the documentation data.

Within the context of Geospatial Data Infrastructure (GDI), cultural heritage data could be introduced as framework data and be integrated with other geospatial data sets and information. The cultural heritage framework data, when combined with other data sets, could be useful in providing information to be used in addressing complex social, environmental issues facing different communities in the country. For instance, use of a GDI would ensure that documented cultural sites and monuments are preserved during the expansion and development of urban centers by creating buffer zones around such sites and monuments.

To instil a sense of pride and belonging as well as develop effective community participation, the National Museums of Kenya could make use of the 3D models and animations to foster awareness in the general public through documentaries. These could also be used in schools and other institutions of learning. Furthermore, trial reconstruction of partly ruined or extinct monuments could be carried out using such 3D models.

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## Appendix A

**LINK TRAVERSE FOR OLD P.C'S OFFICE BUILDING**

**DATUM COORDINATES FOR THE TRAVERSE CONTROL POINTS**

| | EASTING (m) | NORTHING (m) |
|---|---|---|
| TR4 | -20 462.13 | -142 634.59 |
| TR5 | -20 384.87 | -142 594.76 |
| RY1 | -20 385.42 | -142 600.79 |

| | | | Unbalanced | |
|---|---|---|---|---|
| Course | Length | Bearing | ΔX | ΔY |
| TR5 - GR1 | 383.98 | N 14° 11' 37.0" W | -94.151 | 372.254 |
| GR1 - GR2 | 49.06 | N 14° 25' 19.0" E | 12.218 | 47.512 |
| GR2 - GR3 | 33.87 | N 64° 29' 08.0" E | 30.57 | 14.59 |
| GR3 - GR4 | 28.54 | S 33° 37' 13.0" E | 15.802 | -23.766 |
| GR4 - GR5 | 122.97 | S 55° 25' 53.0" W | -101.262 | -69.774 |
| GR5 - GR6 | 238.65 | S 02° 09' 25.0" E | 8.982 | -238.481 |
| GR6 - TR4 | 151.13 | S 19° 29' 49.0" E | 50.44 | -142.462 |
| | | | | |
| Sum | 1008.2 | | -77.4 | -40.126 |

Misclosure in ΔX = -77.400 - -77.260 = -0.140
Misclosure in ΔY = -40.126 - -39.830 = -0.296

| Balanced | | | Coordinates | |
|---|---|---|---|---|
| ΔX | ΔY | Point | X | Y |
| -94.097 | 372.367 | TR5 | -20 384.87 | -142 594.76 |
| 12.225 | 47.526 | GR1 | -20 478.97 | -142 222.39 |
| 30.574 | 14.600 | GR2 | -20 466.74 | -142 174.87 |
| 15.806 | -23.758 | GR3 | -20 436.17 | -142 160.27 |
| -101.245 | -69.738 | GR4 | -20 420.36 | -142 184.02 |
| 9.015 | -238.411 | GR5 | -20 521.61 | -142 253.76 |
| 50.461 | -142.418 | GR6 | -20 512.59 | -142 492.17 |
| | | TR4 | -20 462.13 | -142 634.59 |

**Linear Misclosure = 0.328**
**Relative Precision = 1 in 3,100**

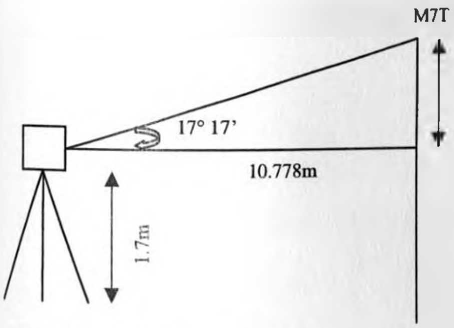
**Adjusted Observations**

| Course | Distance | Bearing |
|---|---|---|
| TR5 - GR1 | 384.07 | N 14° 10' 54" W |
| GR1 - GR2 | 49.07 | N 14° 25' 32" E |
| GR2 - GR3 | 33.88 | N 64° 28' 26" E |
| GR3 - GR4 | 28.54 | S 33° 38' 10" E |
| GR4 - GR5 | 122.94 | S 55° 26' 27" W |
| GR5 - GR6 | 238.58 | S 02° 09' 56" E |
| GR6 - TR4 | 151.09 | S 19° 30' 36" E |

# Appendix B

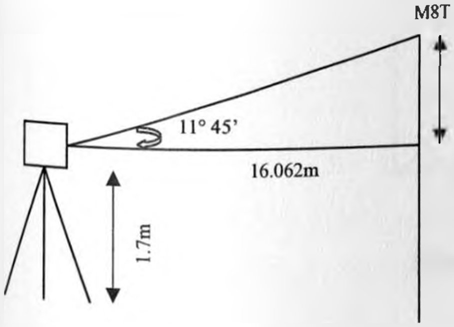
## COMPUTATION OF COORDINATES OF FEATURES ON THE BUILDING

| STATION | LENGTH | WCB | DN | DE | EASTING (m) | NORTHING(m) |
|---|---|---|---|---|---|---|
| @ GR1 | | | | | -20 478.97 | -142 222.43 |
| M2 | 27.838 | 51° 05' 04" | 17.49 | 21.6 | -20.457.37 | -142 204.94 |
| M3 | 36.578 | 21° 35' 45" | 34.01 | 13.46 | -20 465.51 | -142 188.42 |
| | | | | | | |
| @ GR2 | | | | | -20 466.72 | -142 174.81 |
| M4 | 12.693 | 164° 13' 17" | -12.21 | 3.45 | -20 463.27 | -142 187.02 |
| M5 | 7.138 | 112° 13' 03" | -2.7 | 6.61 | -20 460.11 | -142 177.51 |
| M6 | 5.666 | 94° 11' 10" | -0.41 | 5.65 | -20 461.07 | -142 175.22 |
| W2 | 4.859 | 81° 28' 18" | 0.72 | 4.8 | -20 461.98 | -142 174.09 |
| W1 | 13.977 | 180° 36' 08" | -13.98 | -0.15 | -20 466.87 | -142 188.79 |
| | | | | | | |
| @ GR3 | | | | | -20 436.15 | -142 160.21 |
| M7 | 10.778 | 230° 18' 31" | -6.88 | -8.29 | -20 444.44 | -142 167.09 |
| M8 | 16.062 | 194° 32' 39" | -15.55 | -4.03 | -20 440.18 | -142 175.76 |
| M9 | 25.394 | 193° 57' 29" | -24.64 | -6.12 | -20 442.27 | -142 184.85 |
| M1 | 40.075 | 193° 42' 29" | -38.93 | -9.5 | -20 445.65 | -142 199.14 |




Height of Building = 10.778 * tan 17° 17' + 1.7
= 5.0m

*Figure B.1: Height of Building from Point M7.*




Height of Building = 16.062 * tan 11° 45' + 1.7
= 5.0m

*Figure B.2: Height of Building from Point M8.*

M7T and M8T are points on top of the building.

# Appendix C

## MATHEMATICAL FORMULATIONS IN CLOSE RANGE PHOTOGRAMMETRY

The contents of this appendix are drawn from Karara et al (1980), Moffit & Mikhail (1980), and Cooper & Robinson (1996).

In photogrammetry, the position of a point in space is defined by a 3D Cartesian coordinate system. This coordinate system can have its origin, scale, and orientation arbitrarily defined. The mathematical models in photogrammetry are based on the principle (geometry) of a central perspective projection, i.e. the single camera geometry, the geometry of two cameras, and the multi-station convergent geometry.

### C.1 Single Camera Geometry

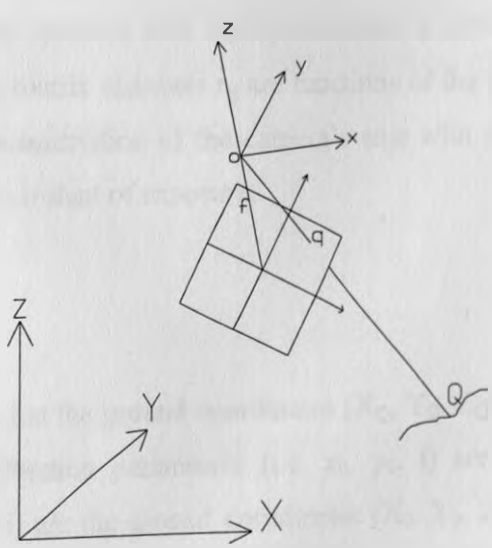



*Figure C.1: Single Camera Geometry.*

In Figure C.1, the ground coordinate system is defined by the XYZ axes, whereas the photo coordinate system is defined by the xyz axes. The position of the perspective centre o in the ground coordinate system and in the photo coordinate system is given as: ($X_0$, $Y_0$, $Z_0$), and ($x_0$, $y_0$, $z_0$) respectively. The point Q ($X_Q$, $Y_Q$, $Z_Q$) on the earth's surface is imaged as point q ($x_q$, $y_q$, -f) on the photo, where f is the focal length of the camera. The points o, q, and Q taken to be collinear, thus forming the basis for the formation of the collinearity condition equations in photogrammetry. Collinearity is the condition in which the exposure station of any photograph, any object point in the ground coordinate system, and its photographic image all lie on a straight line Moffit & Mikhail (1980). The equations that express the collinearity condition are the collinearity condition equations, given as;

$$x_q = -f\frac{[r_{11}(X_O - X_Q) + r_{12}(Y_O - Y_Q) + r_{13}(Z_O - Z_Q)]}{[r_{31}(X_O - X_Q) + r_{32}(Y_O - Y_Q) + r_{33}(Z_O - Z_Q)]},$$

$$y_q = -f\frac{r_{21}(X_O - X_Q) + r_{22}(Y_O - Y_Q) + r_{23}(Z_O - Z_Q)}{r_{31}(X_O - X_Q) + r_{32}(Y_O - Y_Q) + r_{33}(Z_O - Z_Q)}, \quad \text{....Equation C.1}$$

where $r_{ij}$ $\{ij = 1,2,3\}$ are the elements of the orthogonal matrix that rotates the photograph's coordinate system's axes into parallelism with the ground coordinate system. The orthogonal matrix elements $r_{ij}$ are functions of the three components ($\omega$, $\phi$, $\kappa$), which define the orientation of the camera's axis with respect to the ground coordinate system, at the instant of exposure.

**Space Resection**

In Figure C.1, suppose that the ground coordinates ($X_Q$, $Y_Q$, $Z_Q$) of the imaged point q, and the camera calibration parameters (i.e. $x_0$, $y_0$, f) are known. Hence, the unknowns in equation (i) are the ground coordinates ($X_0$, $Y_0$, $Z_0$) of the perspective centre o, and the three components ($\omega$, $\phi$, $\kappa$) which define the orientation of the camera's axis. These elements (i.e. $X_0$, $Y_0$, $Z_0$, $\omega$, $\phi$, and $\kappa$) are also known as the six elements of exterior orientation. If three control points (such as Q) are imaged on the photograph, they can be used to generate the six equations necessary for the determination of the unknowns. These control points should be well distributed within the coverage of the photograph so that they constitute a good intersection at o.

However, the collinearity condition equations are non-linear and need to be linearized using the Taylor's theorem, before being used to solve for the unknowns.

If more than three control points are available, then a least squares (iterative) solution can be used to resolve for the unknowns, which forms a statistically rigorous computation. This process of determining the six elements of exterior orientation (i.e. the spatial position and orientation of a photograph with respect to the ground coordinate system) is called space resection.

## C.2 The Geometry of Two Cameras

### Space Intersection

Suppose that a point on the ground (say S), is imaged on two photographs. Assume further, that the six elements of exterior orientation of both photographs have already been resolved individually (i.e. space resection), and the measured photo coordinates of S in photo 1 and 2 are given as ($x_1$, $y_1$) and ($x_2$, $y_2$) respectively. In this case the collinearity condition equation C.1 can be used to compute the ground coordinates ($X_S$, $Y_S$, $Z_S$) of S, which constitute the unknowns in the equation. Since, in this case, the number of unknowns (three) is less than the number of the equations (four), the equation is solved iteratively using the least squares solution.

### Relative Orientation using the Coplanarity Equations

Relative orientation (RO) is the process by which a pair of overlapping photographs are related to one another in some arbitrary (coordinate) space to correspond with their co-orientation at the time of photography. This process solves for five orientation elements (i.e. three rotational and two translational elements), resulting in a 3D model in an arbitrary space and at an arbitrary scale. Coplanarity is the condition in which the vector joining the two perspective centers (of the two photographs), the object point on the ground, and the two rays that image this point on the photographs all lie in the same plane (i.e. they are coplanar). The equations which express this coplanarity condition are given as,

$$\det\begin{vmatrix} 1 & x_1 & x_2^1 \\ by/bx & y_1 & y_2^1 \\ bz/bx & -f & z_2^1 \end{vmatrix} = 0 \qquad \text{..... equation C.2}$$

where ($x_1$, $y_1$, -f) are the photo coordinates of the imaged point on photo 1; ($x_2^1$, $y_2^1$, $z_2^1$) are the photo coordinates of the imaged point in photo 2 (rotated to be in parallelism with the coordinate system of photo 1); and (bx, by, bz) are the components of the vector that joins the two perspective centers of the two photographs. The unknowns in equation C.2 are (by/bx), (bz/bx), $\omega$, $\phi$, and $\kappa$, which form the five elements of relative orientation of photo 2 with respect to photo 1. The iterative least squares method is used to resolve for the unknowns.

Once the elements of relative orientation have been determined, equation C.2 can be used to compute 'model coordinates' of any other points in the photographs.

## C.3 Multi-Station Convergent Geometry

### Bundle Adjustment

In a multi-station convergent geometry, a point on the ground may be imaged on more than two photographs. Subsequently, all the collinearity condition equations taken together form a set of equations which is called the functional model of the photogrammetric system:

$$F(x, b, a) = 0 \qquad \text{...... equation C.3}$$

where, x is a vector of the parameters to be estimated, b is a vector of the measured photo coordinates, and is a vector of the elements whose values are known and are considered to be constant. The process of simultaneously evaluating the coordinates of points of interest, and the exterior orientation parameters of the photographs using (iterative) linearized least squares based on the collinearity equations is known as bundle adjustment. When the parameters that define the camera's calibration are also evaluated, the process is called a 'self-calibrating' bundle adjustment.

## Appendix D

### Technical Specifications of Cvrax 2500 Laser Scanner

*(Source: Santala & Joala (2003))*

| | |
|---|---|
| *Single point accuracy:* | |
| Position | ±6 mm @ 1.5 m – 50 m range, 1 Sigma |
| Distance | ±4 mm, 1 Sigma |
| Angle | ±60 micro-radians |
| | |
| *Modeled surface precision* | ±2 mm |
| *Spot size* | ≤6 mm from 0 - 50 m |
| *Range* | Maximum up to 100 m |
| *Scan rate* | 1000 points/sec |
| *Scan density* | Independently selectable vertical and horizontal point-to-point measurement spacing, 0.25 mm minimum point-to-point spacing (at 50 m) in both direction. |
| *Field of view* | 40° vertical and 40° horizontal |
| *Number of measured points* | 1000x1000 points/scan |

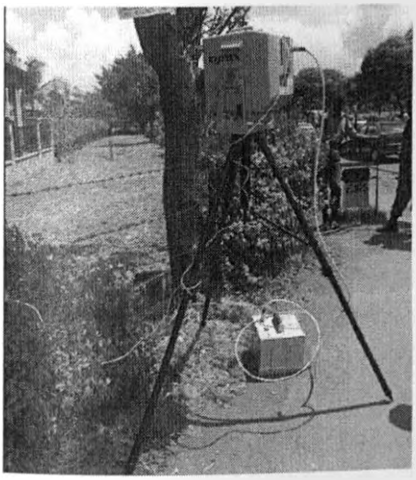
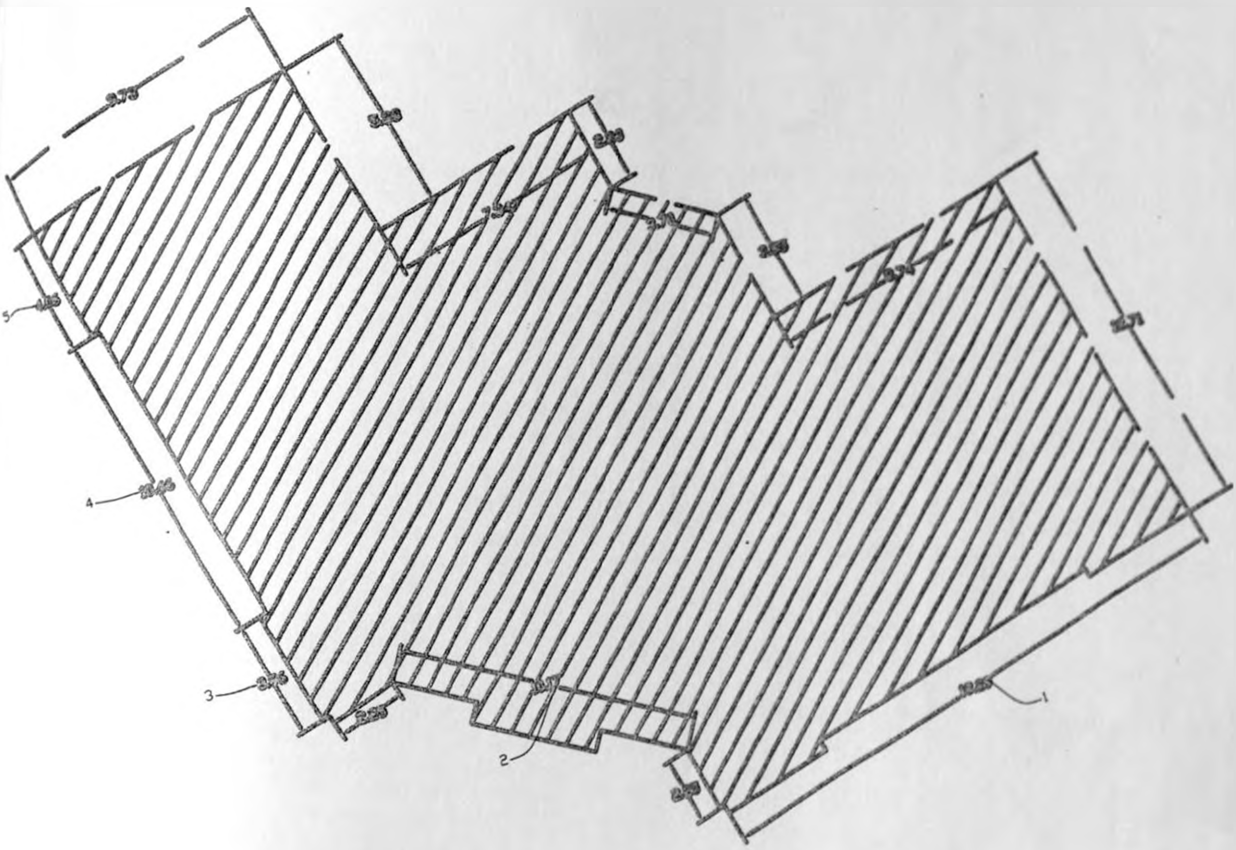


***Figure D.1: Cyrax 2500 laser scanner***

# Appendix E: 2D Plan of the old PC's Office Building



Scale 1:200



| Laser Scan Vs Tape Measurements | | | |
|---|---|---|---|
| Length | Tape (m) | Laser Scan (m) | Difference |
| 1 | 18.40 | 18.29 | 0.11 |
| 2 | 10.14 | 10.17 | -0.03 |
| 3 | 4.10 | 3.96 | 0.14 |
| 4 | 10.40 | 10.46 | -0.06 |
| 5 | 4.20 | 4.06 | 0.14 |