US Department of the Interior
National Park Service
National Center for
Preservation Technology and Training
Publication No. 1996-05

Development and Implementation of a Rapid Low-Cost Photogrammetric Data Archival System for Artifact and Osteological Inventory

Anne Gisiger
Eben S. Cooper
Yew Yuan
W. Fredrick Limp

Center for Advanced Spatial Technologies
University of Arkansas, Fayetteville

Final Report
NPS Grant Number: MT-0424-4-NC-22
National Center for Preservation Technology and Training

March 1996

Funding for this report was provided by the National Park Service's National Center for Preservation Technology and Training, Natchitoches, Louisiana. NCPTT promotes and enhances the preservation of prehistoric and historic resourcesin the United States for present and future generations through the advancement and dissemination of preservation technology and training.

NCPTT's Preservation Technology and Training Grants program develops partners in non-profit organizations, universities and government agencies throughout the United States to complete critical preservation work and lends significant support to developments in the conservation and preservation community.

Table of Contents

ABSTRACT

For as long as institutions and individuals have been obtaining, collecting and storing prehistoric and historic materials they have struggled to find and implement a good, usable, reliable and transferable method for increasing the usefulness of their collections. In the past the public and researchers would need to travel to a museum or other collections repositories to study materials in any detail, particularly to obtain measurements of the objects. However, travel was costly and the measurement process often exposed the object to damage through handling. In other cases objects that have been placed in public museums or repositories may no longer be accessible for such studies since they may be removed as a result of repatriation.

Modern technical developments in computerized, softcopy photogrammetry now can address many of these problems. This report discusses the feasibility and processes necessary to utilize photogrammetric techniques and photogrammetric software in order to be able to gather metric data from softcopy three-dimensional images. A non-metric 35-mm camera, scanner and software system are used to generate color stereo images from which metric data can be retrieved. Our study indicates that such a system can yield measured results from the images only that are well within an acceptable range of error. These results demonstrate the great potential of photogrammetry and modern technology for archiving images, collecting measurements and analyzing artifacts that might not physically be available for study in the future. In addition it suggests consideration of a new approach to the distribution or publication of information about collections or objects. This would involve the distribution of stereo digital imagery, on CD ROM or on the Internet. Researchers who desire detailed measurements of any illustrated object could readily obtain it from the imagery alone.

This research was made possible through Grant MT-0424-4-NC-22 from the National Center for Preservation Technology and Training (NCPTT), and through the use of softbench photogrammetry equipment and software provided by the Intergraph Corporation to the Center for Advanced Spatial Technologies.

List of Figures

List of Tables

INTRODUCTION

Due to growing requirements of repatriation as well as the need for data transfer and analysis there is a critical need for a rapid, low cost method of recording archaeological artifacts and osteological materials in a manner that will allow retrieval of metric information at a later time. Such methods can also be useful in field situations where collections cannot easily be brought to the lab (i.e. work abroad) and also opens the door to the utilization of digital images as teaching tools. Were such a method available, it would also fundamentally alter the nature of publication as it would be possible to obtain measurements from the published digital images. While there are many reliable methods of extracting data from artifacts, many times these methods are time consuming or costly, especially when considering the task of recording a large collection. While physically measuring artifacts might be best, it is impossible to record everything in a manner which will answer unknown research questions of the future. Nothing can replace the direct handling and viewing of archaeological material but alternative methods for the recordation of material culture are increasingly important. Because hardware and software costs are rapidly declining and the power and storage capacities of computers are rapidly increasing, the archaeologist or museologist now has the ability to process and store digital images. As technology advances, one must look to the future and possible methods of recording, comparing and sharing data. Digital images, which are now of a very high quality, should be considered as one such method. After photographs are scanned into a digital format (or obtained directly through use of a charge-coupled device or CCD camera) they can be easily transferred to and utilized by fellow researchers. More and more data are being made accessible via the Internet with tools such as the World Wide Web (WWW), File Transfer Protocol (ftp), and gopher (a bulletin board facility). The WWW already gives access to documents being served from all over the world, and museums are rapidly adopting the concept of “virtual exhibits”. WWW pages can also be used as catalogs of compressed digital images from which one can choose and download data. Therefore, an extended catalog of stereo pairs could be made available for users to download, view, and measure locally with a photogrammetry software package. While this would require substantial computer disk space, hard disk pricing is dropping rapidly. An alternative means to distribute data is by storing images on CD-ROMs that could be loaned or served via the Internet from an institution through the use of a CD jukebox.

The purpose of this research is to develop a rapid, low cost method for reliably recording artifact information in a manner that can be accurate for analysis in the future when the actual physical artifacts may not be available. This method should also be one that is usable for the professional anthropologist who is not a specialist in photogrammetry. By utilizing this process, not only are valuable photographic images produced but it is also possible to view the artifacts on the computer screen as high resolution three-dimensional images and to take measurements of artifacts and artifact features.

BACKGROUND

Being able to collect accurate three-dimensional measurements or to generate a permanent record from which information can be extracted is crucial to the field of archaeology. This section will review some of the methods currently available.

Photography can provide a relatively permanent record of things of a transient nature, such as an object or location which can be inspected only for a short time or the short-lived outcome of an experiment. In the field, archaeologists use it to record the position and appearance of *in situ* artifacts or the profiles of trench walls. Similarly, for museums photography can be one of many ways to document collections.

Besides providing information about the general shape and color of an artifact, photographs can also, if a scale measure is present in the image, provide rough estimates of the object's dimensions such as width and height. However, accurate measurements can be obtained only for features located within a single plane or depth and thus are useful only for basically flat surfaces such as walls and floors. Eiteljorg describes the method he utilized in Pompeii to generate precise drawings of the walls of a sanctuary (1994). Each wall was photographed along with at least four survey points of known two-dimensional locations. Due to various factors, such as lens distortion and film curvature, a precise representation of an object cannot be collected directly from a photograph. Instead Eiteljorg used a Computer-Aided Design (CAD) software to digitize the desired features and correct their positions by applying a mathematical transformation based on the coordinates of the survey points. This process is called image rectification. This technique is simple and inexpensive; however, when a feature spans several levels of depth, each one has to be drafted and rectified separately.

Measuring and recording three-dimensional information is a non-trivial task. In archaeological field settings, multiple rulers, plumb bobs, and other similar combinations are used. While suitable for field measurements, these methods are inadequate for small objects or when high accuracies are required. The most common method is to measure angular and planar distances with an instrument and feed them into some trigonometric equations to generate the desired three-dimensional data. For extremely precise results, such as those required when designing an airplane or the space shuttle, a complex method involving two or more survey theodolites can be used. Neither method is straightforward.

Various tools exist for gathering three-dimensional information. Scott (1982) tested two of them: the reflex metrograph and the reflex microscope. The metrograph allows the precise drawing of cross-sections and contour lines and has great potential for drawing *in situ* artifacts. Connected to a micro-computer and with the addition of a secondary mirror, the reflex metrograph allows one to take three-dimensional measurements all around an object without having to move the latter. The reflex microscope functions in the same manner and can achieve precision up to a tenth of a millimeter. It has been used, for example, to quantify teeth wear (Adams and Tregidga, 1992). Scott recommends these instruments as they are very easy to use and do not require any prior training.

A more technologically involved method uses a red-green-blue (RGB) white light laser scanner developed at the National Research Council Canada/Autonomous Systems Lab. Baribeau (1993) describes its abilities to efficiently and precisely record the shape, volume, and color of an object. Three-dimensional data, with accuracies higher than 25 micrometers, is collected by a laser, which scans an object and records for the scanned area its distance to the camera (i.e. the z value or depth), as well as its color, stored as values of red, green, and blue. The x and y coordinates are derived respectively from the speed at which the scanning head and the camera are moved. The complete coverage of an object is easily obtained by rotating the object 360 degrees during the scanning. A graphic workstation then allows one to view the recorded objects at various elevations, angles, and scales, in full color or just as a wireframe (Baribeau et al., 1992). A major advantage of this system is its capability to reconstruct the recorded object using a three-dimensional output device. Baribeau describes scanning a 10 centimeter-long engraved lead plate, which was later reproduced with a computer-driven drilling machine. The replica showed “surface details as small as 10 micrometers” (Baribeau, 1993: 43). Such a technique holds many promises for the reconstruction of petroglyphs, the assessment of the accuracy of replica or to monitor changes in shape or color, and can provide invaluable data about the impacts of conservation treatment, transportation, and deterioration of collections. This system seems to be appropriate for major museums with large collections since they would most likely have the needs and resources necessary for its purchase and operation.

A more broadly applicable set of methods to obtain three-dimensional measurements is the primary concern of a discipline called photogrammetry. Although not yet widely known, this field has enormous potential for most archiving or recording needs. The photogrammetric theory encompasses two different methodologies. One, stereo-photogrammetry, is based on the human capability to see three-dimensionally; the other, called monoscopic or convergent photogrammetry, relies on a set of mathematical equations to compute the third dimension. Since it was the method used for this study, stereo-photogrammetry will be the focus of the discussion below.

Stereo-photogrammetry is based on the concept of stereo-viewing, which derives from the fact that human beings naturally view their environment in three dimensions. Each eye sees a single scene from slightly different positions. The brain then “calculates” the difference and “reports” the third dimension. This process can be easily simulated by taking two photographs of the same object or scene with two identical cameras separated by a certain distance. With some

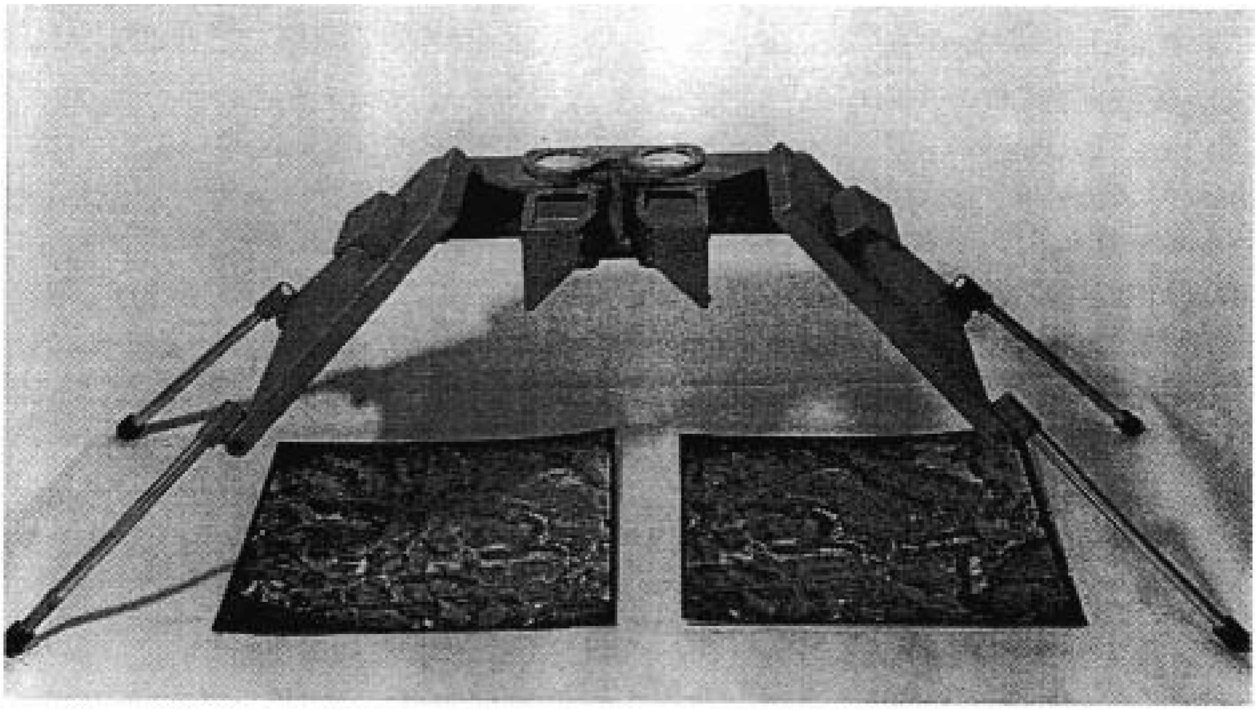


Figure 1. A mirror stereoscope

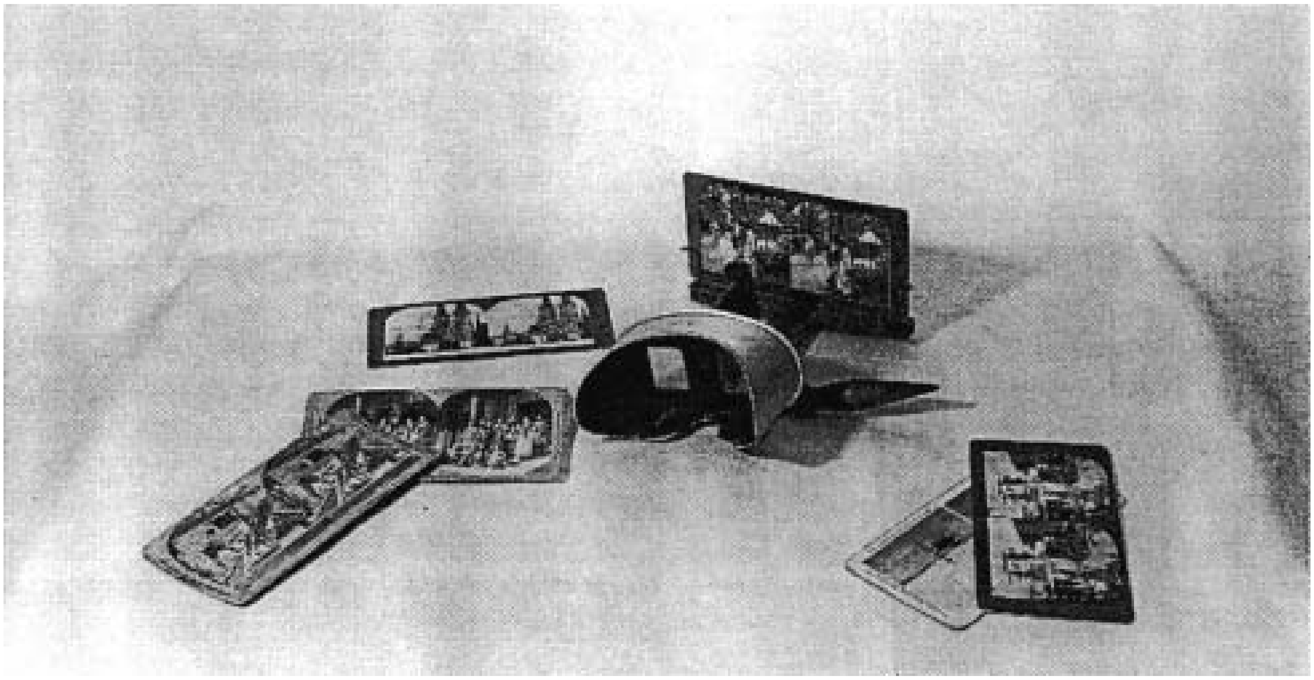


Figure 2. A parlor stereoscope

eye-training, one can perceive me three-dimensional effect by placing me two photos side by side and focusing each eye on its corresponding image, i.e. the left eye looking at the photo taken with the left camera and the right eye at that taken with the right camera (Avery and Berlin, 1992). The use of special glasses or binoculars, as found on a mirror stereoscope, will facilitate this exercise by allowing each eye to see only one picture (see figure 1). The old parlor stereoscopes or print viewers, which were sold at the turn of the century for the purpose of viewing stereo postcards operate in the same manner (see figure 2). Similarly, the View-Master viewers, marketed as toys, are binoculars allowing one to view stereo images mounted on a disk. Several systems designed to create and view one's own stereo images are available to the general public (Alpers, 1995). They - are ideal as visual tools, allowing to effectively present three-dimensional data.

Photogrammetry's purpose is that of refining the concept of stereo-viewing to allow not only the perception of depth but also the ability to accurately render distances and depth, therefore providing a mean to record reliable three-dimensional metric information. It has been defined by the American Society of Photogrammetry as "the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns" (Wolf 1983:1).

Accurate representation of a three dimensional surface can be achieved if the overlap between the left and right photos represents 50 to 80 percent of their surface (see figure 3). Sixty percent is the amount of overlap recommended by professionals. It exaggerates the perception of depth and therefore facilitates the acquisition of good depth measurements.

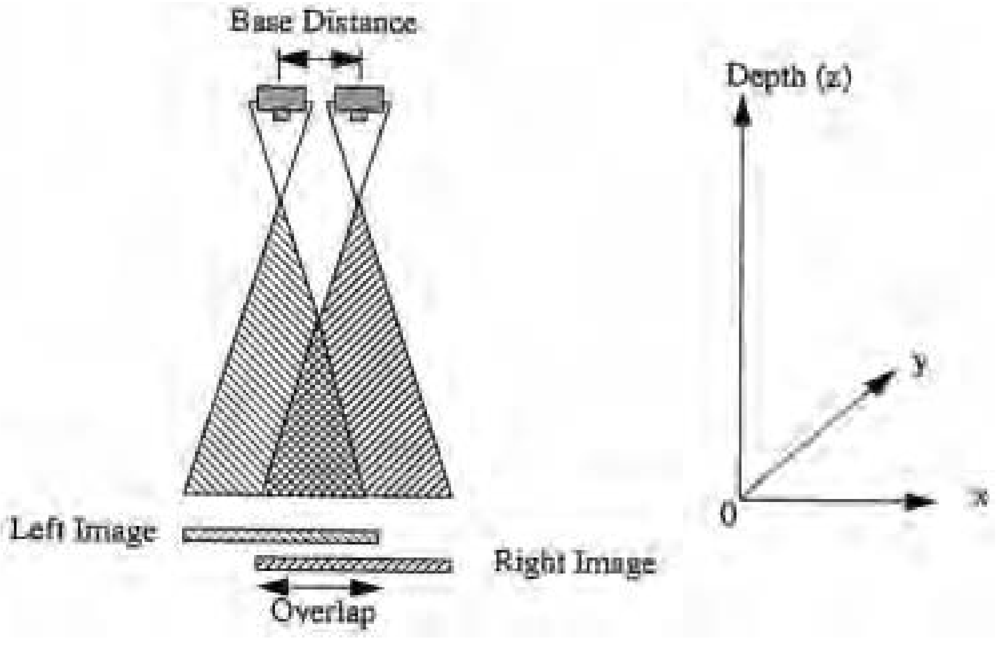


Figure 3. Photographs taken with a 60 percent overlap

Today, photogrammetry is being used primarily to characterize the earth's surface and to generate digital elevation models (DEMs) and orthophotos which, in turn, assist in the production of maps. The power of photogrammetry relies primarily on its ability to provide very precise three-dimensional information from a remote location. For example, maps are being produced solely from aerial photographs, except for the collection of reference survey points which has to be done in the field. If one uses a Global Positional System, all survey points can be obtained by one person during a single trip, therefore empowering aerial photogrammetry even more.

Aerial stereo images are produced by taking strips of overlapping images from an airplane. Photographs are taken along the flight line at known regular intervals, so as to generate a 60 percent overlap. Figure 4 shows a typical flight plan. Photos 1 through 4 are first taken with a 60 percent overlap, then the plane turns back to shoot a second strip of photos. Overlapping strip 1 and 2 by 60 percent insures that photos 4 and 5, 3 and 6, 2 and 7, and 1 and 8 are stereo pairs as well.

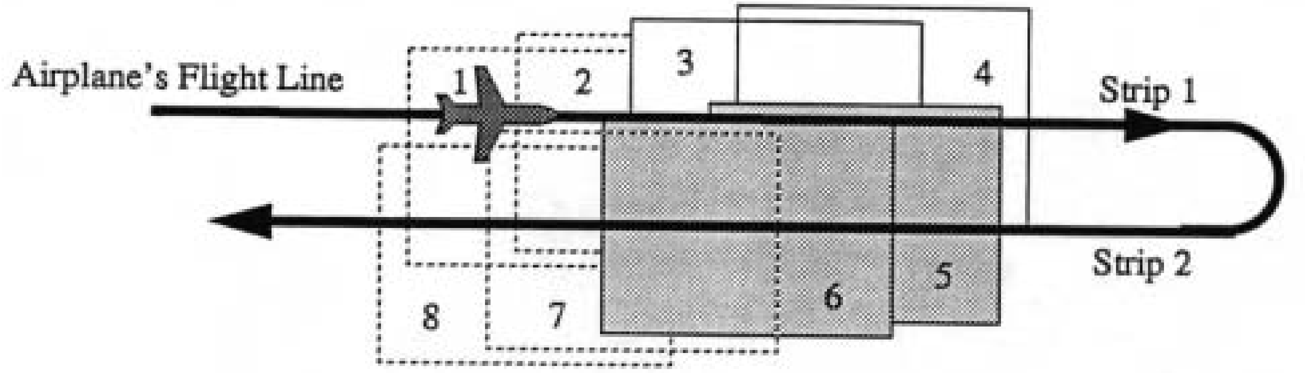


Figure 4. Generating aerial stereo images

Two kinds of information can be extracted from stereo pairs: quantitative data such as distances, elevations, angles, areas and volumes, and qualitative data such as feature and pattern identification. These are called metric and interpretative photogrammetry respectively. One can anticipate the value such a technique could have for archiving archaeological artifacts. But because of the costly and highly specialized equipment required, photogrammetry has been, until very recently, a field restricted to trained professionals. Today, however, several software packages available either on personal computers or on powerful graphic workstations allow anyone to process and analyze stereo images.

A. CLOSE-RANGE PHOTOGRAMMETRY

Stereo-photogrammetry can also be used to gather information at any scale. Photogrammetry applied to non-aerial applications is called terrestrial, or close-range if the camera-object distance is less than three hundred meters (Wolf, 1983: 477). Close-range photogrammetry has enormous potential for any kind of project involving the collection of three-dimensional information. The projects, in the fields of archaeology, architecture, historical preservation and others, discussed below reflect the breadth of disciplines which can benefit from photogrammetry.

1. Surveying monuments and buildings

The very first photogrammetric experiments were made on monuments in 1840 by Albrecht Meydenbauer, a German architect (Carbonnell, 1989:321). At the present time, architectural photogrammetry is being used intensively in France (Dallas and Carbonnell, 1992), Greece (Potsiou et al., 1992), Italy (Birardi, 1992), and eastern Europe (Kempa and Schlüter,1992; Gutu, 1992) to survey national monuments and sites or to gather information prior to starting some restoration work. The recorded information can also be used to generate three-dimensional computer-aided design (CAD) models of a monument (Gutu, 1992). At a photo scale of 1:50, a building’s facade photographed with a standard photogrammetric camera can be measured within one to two centimeters of accuracy (Carbonnell,1989).

In 1990, the University of Milan conducted a photogrammetric survey of the Tower of Pisa in an attempt to analyze the impact of the “leaning process” on individual stories of the tower (Baj et al., 1992). A total of sixty-six stereo photographs were taken from twelve camera positions located along a circle centered on the tower. The camera was placed in an elevator twenty-three meters above the ground, to allow the whole tower to be photographed. The structural features were then digitized and a CAD model of the tower constructed.

Photogrammetry also has the advantage of gathering information quickly and objectively. Unlike a person, a camera captures all of the visible information and not just what seems important. Moreover, stereo-viewing of carefully taken images shows more detail than single photos, for example helping to prevent the misinterpretation of shadowed areas. For these reasons, the International Committee for Monuments and Sites (ICOMOS), in 1987, adopted a resolution stating that all World Heritage Sites should be recorded photogrammetrically (Dallas and Carbonnell, 1992). In 1989, one hundred sites were identified as having been at least partially recorded with photogrammetric methods. A list of World Heritage Sites recorded since the ICOMOS resolution is given by Dallas and Carbonnell (1992:425). Among them are the Cahokia Mounds (U.S.A.), Teotihuacan (Mexico), Tikal (Guatemala), and Rome’s historic district.

Similarly, the Abu Simbel temple (Egypt) was completely surveyed prior to its transportation and relocation up-stream along the Nile.

All the above examples used professional metric survey cameras suited for terrestrial applications. Novak, on the other hand, attempted a similar experiment using a still video camera, i.e. a regular video camera equipped with a charge-coupled device(CCD) to directly record an image in digital format (1992). Although he had not tested this technique on a real project, he expected to obtain an accuracy of four centimeters.

2. Museum research and rock painting

Close-range photogrammetry has great potential for the analysis and archiving of smaller objects too. Azarpay, for example, demonstrated that three large Gudea statues from Mesopotamia were manufactured using a “consistent system of proportions” (1990: 662). In order to obtain “objectively verifiable measurements of proportional ratios through calculation of coordinates in an arbitrary coordinate system,” he had a professional take stereo images and derive measurements for the various sections on each statue.

Similarly, in Brazil an attempt was made to record rock paintings using photogrammetry instead of the painstaking process of manually tracing wall features. This method proved to be a viable one to quickly and accurately record rock shelters (Mendonça, 1992).

3. Modelling surfaces

Another useful application is that of generating digital elevation models (DEMs) from large scale photos. Kempa, for example, started an experiment to monitor the weathering of carved stones on buildings (1992). His intent was to generate a DEM for a chosen set of stones on a yearly basis. Since he obtained measurements accurate within 0.1 to 0.3 mm for the first year, he expects to be able to continue to record changes in the stone surface.

In another example, the Technical University of Berlin tested the feasibility of monitoring changes in agricultural soil micro-relief due to rain (Helming, 1992). Different intensities of rain were simulated and stereo pairs taken at various steps in the process. Comparisons of the obtained DEMs allowed a better understanding of how rain affects soils of various hardness.

4. Biostereometrics and medical applications

The medical field already draws considerably from photogrammetry. For instance, combining the techniques of X-ray photogrammetry and computed tomography (CT) allows the creation of a system simulating a cerebral biopsy. The veins and arteries are photographed in stereo and CT is used to create cross-sectional images of the patient's brain. A simulator then allows the surgeon to establish the best path to use for the removal of a tumor. This method has been used successfully, i.e. tumors have been removed without causing internal bleeding (Boulianne et al., 1991). Along a different line, photogrammetry has been used to identify the variability encountered in the shape of the human face. This was done to assist in the design of protective head gear. For each subject, thirty-seven anatomical landmarks and seven anatomical arcs were identified and marked on the skin. The data returned was compared to manual measurements and found to be within one millimeter. Although this technique is time consuming, it provides data faster and in a more consistent manner than manual methods (Coblentz, Mollard and Ignazi, 1991).

5. Underwater photography

Photogrammetry can also be applied to underwater applications. Fryer and Fraser (1986) demonstrated that semi-metric and metric cameras can be reliably calibrated to allow the identification and positioning of objects. They anticipate that the calibration of standard cameras might produce accuracies of at least 1 to 5000, and possibly 1 to 8000 if the image quality is good.

6. Monoscopic/ convergent photogrammetry

All the applications described above use two stereo images taken from parallel camera orientations, also known as stereo-photogrammetry. There exists another type of photogrammetry referred to as monoscopic or convergent. It is characterized by the use of two or more cameras positioned at an angle converging towards the object of interest. This method is considered more versatile and more accurate than stereo-photogrammetry. Fraser reports repeatable accuracies of 1 to 1,0000,000 using a large format camera and the software package STARS (1992). Monoscopic photogrammetry is used principally in the field of quality control to take real-time measurements without the intermediate of a picture (Adams, 1989). This method is based on the assumption that if a point is visible in two or more photographs, its three-dimensional location can be computed if the position and orientation of the cameras are known (Wolf, 1983:487). It appears from this definition that monoscopic photogrammetry uses a completely different set of equations than stereo-photogrammetry. It is a more expensive technique since the cameras must be mounted on theodolites for the angle of the camera to be controlled.

The Metrology Norway System (MNS) is a quality control system for the automobile industry (Petersen, 1992). Using two high resolution CCD cameras converging towards an object, an operator is able to obtain in real-time the coordinates, with a 0.1 mm accuracy, of points selected with a light pen or a laser-spot projection system. It can also measure the total body of a car and create a CAD file from it. The CAD file can then be used to automatically check any variation in shape, this can be used to document the creation process of a new prototype, or the deformations occurring during collision testing. When combined with computer-vision and digital image processing, monoscopic photogrammetry becomes a means to not only perform quality control but also to inspect manufacturing tools. Husen and Benter (1992) describe a system which is able to automatically locate and measure the edges of a cutting tool to identify those which need to be replaced. Two CCDs cameras zoomed in on the cutting tool can provide edge measurements with an accuracy of three micrometers when the edges are well defined (1992:532). Garrison used convergent metric cameras to assist in the field of underwater archaeology (1992). His method produced results at an accuracy of 1 in 2000 units.

7. Photogrammetry in archaeology

In the early eighties, Fussell discussed the potential of photogrammetry for archaeology(1982). Due to the high cost and complexity of the equipment required, she recommended its use only for major projects such as the architectural applications discussed earlier. For smaller endeavors, she encouraged archaeologists to generate stereo images, but only to view them three-dimensionally with binoculars. For those requiring measurements, she recommended the creation of rectified single photos, taking into consideration that only features located within the same level of depth can accurately be measured.

Fussell’s perception regarding photogrammetry, echoing a general belief which existed prior to the computerization of the photogrammetric process, is slowly changing. In 1991, John Burns of the Historic American Building Survey/Historic American Engineering Record of the U.S. National Park Service summarized the advantages and disadvantages of softcopy photogrammetry. The advantages listed are that it can produce accurate drawings to document structures that are too large, inaccessible or dangerous to measure directly, and that film is easy to reproduce and archive. The primary disadvantage is the high cost of photogrammetric cameras and software (Burns, 1991 in Garrison, 1992: 103).

Although the cost of photogrammetric equipment remained an issue in 1991, the need for experienced specialists was not mentioned. Indeed, the recent advent of fully computerized photogrammetric systems is now allowing non-professionals to process stereo images and extract measurements from them without extensive training. This already represents a significant drop in price. In relative terms, full-blown photogrammetric systems remain as expensive as analytical plotters were ten years ago. However, more and more affordable softcopy systems are becoming available on the market, some of them even PC-based. One expensive investment remains, that of a camera specially calibrated for photogrammetric applications. The goal of this project has been to test whether a softcopy system, using pictures taken with a standard 35 mm camera, could produce measurements as good as those one could obtain manually.

B. THE PHOTOGRAMMETRIC PROCESS

Before accurate three-dimensional measurements can be obtained, the stereo images must undergo an elaborate preparation. This section will describe the process briefly.

In essence, photogrammetric theory rests on the assumption that if lens distortions were minimal and the film plane perfectly flat, the scene recorded on the film would be an almost exact proportional representation of the real-life scene, and therefore extremely accurate measurements could be extracted. In reality, many sources of errors affect the accuracy of three-dimensional measurements, and assessing and correcting the percentage of error compounded at every step of the image generation and the processing remains a major concern for the field of photogrammetry. In the case of aerial photographs, cameras are calibrated and fixed inside the plane in a stable position. While in flight, the camera takes pictures at a time interval synchronized with the plane speed to guarantee an average photo overlap of 60 percent (see figure 5).

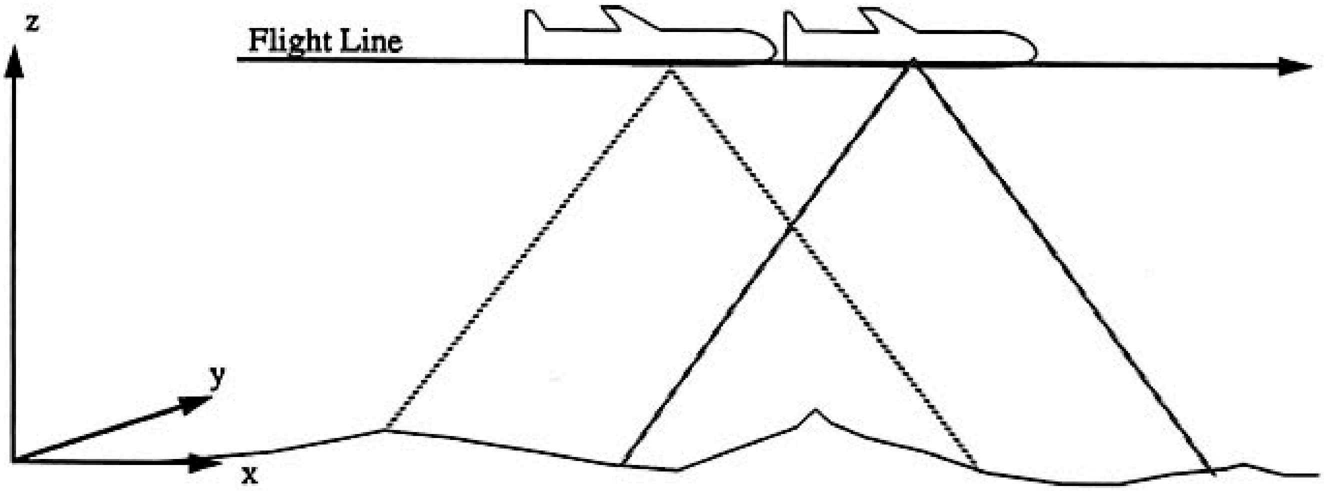


Figure 5. Taking aerial photographs along a flight line

The camera's orientation, assumed to be the same as that of the plane, is expressed in terms of x, y, z coordinates with respect to the ground. If the flying speed remained constant and the plane perfectly stable and parallel to the ground, the stereo photographs could be used without any correcting process. In real life, the trajectory of the plane is bound to be affected by atmospheric conditions. Any departure from a perfectly straight flight line must therefore be corrected before useful measurements can be collected from the photos. This correction is performed as part of a three-step process called orientation.

First, all errors related to the camera, namely the inherent distortion of lenses, must be taken care of. To do so, the camera lens is tested prior to being used so that corrections can be applied to all images taken with this specific camera-lens configuration. After processing of the film, one must assess for each exposure the exact position it had in the camera at the time it was shot. This will insure that the proper lens corrections are applied to the appropriate portion of the image. This process is called “interior orientation” (IO).

Second, the amount by which the airplane departed from its ideal orientation and flight direction must be determined for each photo. These differences are then compensated for so as to produce images suitable for stereo-viewing. This process is called “relative orientation” (RO).

At this stage of the photo preparation, the resulting stereo images can provide an accurate three-dimensional representation of the scene photographed. However, no meaningful measurements can be extracted since no scale or units have yet been assigned. To do so, one needs to have control points or features identifiable on both photographs and for which the three-dimensional coordinates with respect to a chosen reference system are known. These can be obtained using either one of two methods. One can, for instance, visit the field prior to flying an area, to select, measure and mark on the ground the features which will be used as control points. Another option is to first take the pictures and then identify on the photos features which could be easily surveyed in the field. The process of assigning a coordinate system to a stereo model is called “absolute orientation” (AO). Once it is completed, measurements can be extracted from the photographs.

In the past, the processes of orientation and measurement extraction were performed using specialized equipment called stereoplotters. The systems used during the first half of the century implemented all of the 10, RO and AO corrections mechanically and optically. This was achieved using two platforms, one per stereo photo, which could be tilted to recreate for each one the orientation it had at the time of exposure. Depending on the model of plotter used, stereo-viewing was implemented by projecting the two images on the same plane or by using a system of binoculars. Since all processing was done directly on the original hardcopy transparencies, these systems were referred to as analog plotters. There was no standard for the design of these machines and their shape varied greatly depending on the intended purpose. For example, while most were built to deal with only two images, others allowed the operator to process up to eight photos simultaneously (Wolf, 1983:353). All were very difficult to operate and only those who received extensive training were able to obtain consistent results. The complexity and high price of these systems restricted photogrammetry to disciplines for which it was a cost effective alternative, e.g. mapping.

In 1957, U.V. Helava introduced the first partially automated or analytical plotter (Wolf, 1983: 311). Put simply, an analytical plotter consists of a stereoplotter interfaced with a computer program which recognizes the three-dimensional coordinate system of a stereo model. In other words, once the orientation processes are completed, the position of the pointing device on the hardcopy is automatically interpreted in terms of the stereo model’s ground coordinates. Measurements, for instance, are obtained by selecting two endpoints on the image and the distance between them is automatically computed by the computer and expressed in terms of ground coordinates. Similarly, the plotter’s pointing device could be automatically driven to a three-dimensional location by entering the coordinates at the computer console.

The principal difference between analog and analytical plotters is the capability to perform all corrections using mathematical transformations rather than optics. Being able to handle the coordinates of stereo models from within a software program improves and empowers greatly the orientation process not only by enhancing already existing capabilities but more importantly because the photogrammetric process is continuously updated to incorporate the latest developments in computer science, namely the fields of image processing, artificial intelligence, computer-aided design and even the emerging fields of special effects and computer-imaging. Image processing, i.e. the art of manipulating computer images to improve their quality or enhance certain features, for example, was adopted from the very beginning, not only to perform the photo rotations digitally instead of physically, but also to add to the JO process a transformation to correct for film shrinkage or expansion (Wolf, 1983: 314). Such an operation is impossible to perform optically. Therefore, “because they have no optical or mechanical limitations in the formation of their mathematical models, analytical plotters have great versatility “(Wolf 1983: 311). Benefits from this versatility are, among others, the ability to handle oblique, horizontal photography or even radar imagery. Indeed, since all coordinate processing is done using a mathematical model, any image can be handled no matter the focal length used. Analog plotters on the other hand, can typically handle only one focal length.

On analytical plotters, photo-coordinates are translated by the computer into those of the corrected stereo model. Therefore, the operator is working off the original hardcopy images. Today’s systems are completely computer-based and build a corrected digital stereo model as a result of all correction and orientation tasks performed on the original pair. This switch from hardcopy to digital stereo images raised a whole new set of issues, which prompted the creation of a new field, that of softcopy photogrammetry. From the standpoint of a non-photogrammetrist, the single greatest advantage of porting the photogrammetric process to a computer resides in the ease of usage and versatility of the new systems, which will enable a variety of entities to take advantage of photogrammetric-quality measurements. Designed as a window-based software, these systems have a user-friendly interface, where the user is queried for the necessary information while all computations are done transparently. Users without an extensive knowledge of photogrammetry are able to use them efficiently after a short training in the use of the software.

The transition from mechanical to computer-based systems was made possible due to the power of the new CPUs and the lowering cost of memory and disk space. Full-blown photogrammetric software products require fast graphic workstations equipped with fast micro-processors and large memory (RAM) capacity. In order to be efficient, a softcopy system must allow for the storing and processing of large high resolution images. The user must be able to load a stereo model on the computer, display it and to “fly over” the area in real-time while viewing three-dimensionally. A definite advantage over analog systems is the capability to zoom in on a feature or to manipulate the image contrast to improve visibility. Systems offering all these features remain expensive, however, the fact that they are easier to use eliminates the need for hiring expensive specialists.

Current softcopy systems were designed primarily to speed up and simplify the processing of aerial photography. Private firms specializing in the generation of DEMs and orthophotos routinely deal with strips of more than a hundred photographs. Although the computerization of this process has already greatly improved their efficiency, it is expected that advances in computer science will allow the complete automation of the orientation tasks. These are ambitious goals since they require being able to recognize features which could be partially obscured.

Because these systems use digital images, they are able to differently correct individual parts of an image. Optical or analytical systems could not do this and therefore relied entirely on the quality of the camera optics. Software systems, on the other hand, create a new stereo pair from the control point information thereby applying customized corrections. This flexibility has produced good results even with lower-grade camera optics, and has reduced the need for perfectly calibrated lenses. It is this feature which has much promise for low cost artifact measurements via the use of stereo photos.

C. NON-METRIC VS. METRIC CAMERAS

The field of photogrammetry is striving to produce extremely precise three-dimensional measurements which would otherwise be very expensive or impossible to collect directly. In order to guarantee the best results possible, most photogrammetric work is done using specialized cameras referred to as metric. They are characterized by a high geometric quality, fast fixed-focal length lenses, and efficient shutters. Prior to their usage, these cameras are subjected to an in-lab calibration process during which major causes of errors are quantified or corrected (Wolf, 1983: 61-62). Once calibrated, these cameras can provide results accurate within 50 centimeters when measuring tree-height from 1:15000 aerial photos (Warner, 1988 in Warner, 1990:575), or within 2 centimeters for 1:50 scale close-range photographs (Carbonnell, 1989).Reported accuracies reflect the degree to which the photogrammetric solution matches the control points given and do not take into account the errors introduced when measuring the controls.

The accuracy of the results is typically proportional to the quality and price of the camera used. For example, a metric 35 mm camera costs about $10,000, more than ten times the price of a regular single lens reflex (SLR) camera. One using standard off-the-shelf cameras and films would notice a significant loss in accuracy caused by phenomena such as radial-lens distortion, shrinkage and expansion of the film, and the lack of flatness of the film.

Metric cameras are built with very high-quality optics to eliminate most sources of errors that would be caused by optical distortion. Another important component of metric cameras is a film flattening mechanism. If the film is not held flat within the camera magazine, it has a tendency to curl. This causes the object photographed to be recorded on a curved surface, therefore -creating a deformed image. Film "unflatness" if not mechanically corrected, is an important and non-quantifiable source of errors. It is controlled "(1) by applying tension to the film during exposure; (2) by pressing the film firmly against a flat focal-plane glass which lies in front of the film; (3) by applying air pressure into the air-tight camera cone, therefore forcing the film against a flat plate lying behind the focal plane; or (4) by drawing the film tightly up against a vacuum plate whose surface lies in the focal plane" (Wolf, 1983: 67-68). Although none of these techniques compensate completely for the lack of flatness, the distortion remaining is more constant from frame to frame and can be accounted for during the camera calibration process.

Since it is impossible to build a camera completely free of distortion, it should be calibrated prior to being used. This process consists in defining the interior orientation of the camera, i.e. assessing the remaining distortions and measuring the exact location of the fiducial marks. Fiducial marks are cross-hairs etched on the camera's focal plane during manufacturing, which when the film is exposed, print their image on the photograph. These are referred as the photograph's fiducial marks and are used to orient each exposure with respect to the camera interior.

To perform the interior orientation process each photo has to be rotated to reproduce its position in the camera at the time of exposure. Here the hardcopy image is not rotated physically, but rather the computer performs a rotation on the photo coordinates. On a softcopy system, the orientation tasks are performed using mathematical equations, i.e. the user provides the computer with coordinates for several points and the solution best fitting the data is computed. The best solution is achieved by feeding redundant information to the software, i.e. more points than are necessary to come up with a solution. The least squares adjustment is used for that purpose in all three orientation processes, namely the IO, RO, and AO.

A typical aerial photo shows eight marks called fiducials which are imprints of marks located on the camera's focal plane (see figure 6).

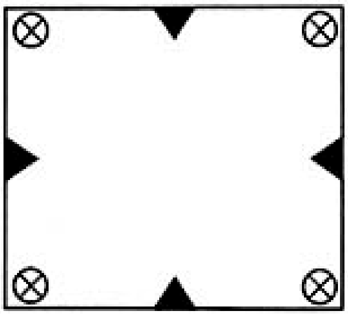


Figure 6. A typical example of fiducial marks

The user enters the coordinates of the marks into the computer by selecting them with the pointing device. The software is also provided with the precise location of the fiducials on the camera's focal plane. The distribution of the original fiducials and their image on the photo would be exactly the same if there were absolutely no deformations due to some lens distortion or variation of the film size. Since in reality, these two phenomena are always present, the photo needs to be transformed using a best fit solution. A typical mathematical model used for this purpose is the affine transformation. It requires six points to return a solution, instead all eight are entered so as to generate redundancy. The solution reached will therefore best fit all eight points. The relative and absolute orientation are performed in a similar fashion.

Purchasing a metric camera is a considerable expense but steps have been taken to insure that all sources of errors are minimized. For metric cameras a report is also provided, indicating the interior orientation parameters to be entered into the analytical plotter or softcopy system. These parameters allow the software to apply the corrections specific to the camera used. If on the other hand, a standard camera is used, its interior orientation is unknown. In the past, these were not recommended for photogrammetric applications, but since the advent of computerized plotters, research studies have been carried out to assess the potential of these models for photogrammetric projects, specifically those requiring a moderate accuracy, i.e. less than 1 unit in 4000. The following section discusses some of their results and the major limitations of standard (non-metric) 35 mm cameras when they are compared to their much more expensive metric counterparts.

1. Lens distortion

The principal source of errors on 35 mm cameras is lens distortion, and, in particular, radial distortion. If a stereo pair is taken of a flat surface and the radial distortion is left uncorrected, one will notice a "hump" in the middle of the stereo model instead of the flat area photographed (Fryer, 1992:596). In other words, the one-to-one correspondence between the object and its image is disrupted. It is possible to perform a relatively simple in-house calibration which will determine the amount of distortion. These could then be fed to the softcopy system or analytical plotter to apply the correction to each photo processed. This method has proved to yield accuracies of 1 to 4000 units (Fryer and Fraser, 1986:75).

2. Need for a film flattening mechanism

As explained above, lack of film flatness is also a critical source of errors. In standard 35 mm cameras “a system of guide and support rails constrain the film longitudinally. There are no specific lateral constraints at either end of the film frame. At one end the film is held by the slot -in the film cassette and at the other by the wind-on-transport sprocket” allowing the film to “bulge towards the front of the camera” (Fryer et al., 1990:18-20). As is the case for lens distortion, the one-to-one correspondence between the object and its image is disrupted. Donnelly estimated the maximum height of this bulge to be 0.6mm (Donnelly, 1988 in Fryer et al. 1990:20-21). Although at first glance, the lack of film flatness seems to be difficult to control or at least assess without an expensive flattening mechanism, further research proved that “film curvature is fairly constant throughout the length of the roll of film” (Donnelly 1988 in Fryer et al.,1990:16) and that the interior orientation process can partially compensate for the effects of film unflatness (Fryer et al., 1990:22) resulting in potential accuracies of 1 to 1000 units. If the recording media is a flat surface such as flattened film or glass plates, results as good as 1 to 4000 units can be expected with a 35 mm camera (Donnelly and Fryer, 1989 in Fryer et al., 1990:26).

3. Defining the film position in the camera body

Photographs taken with a metric camera show eight fiducials which are crucial to the interior orientation process. In non-metric 35 mm cameras, there are no fiducials and, in most cases, corners or edges are used instead. The method recommended by several, including Fryer(1992: 598), is to have a program generate the corners’ coordinates from points placed by the user along the edges. This method is desirable since the corners of the film are often fuzzy or irregular. This is possible only if your system allows this kind of procedure. One can see how not having fiducials will introduce additional error since all interior orientation corrections are done with respect to them.

Using a non-stable film base, such as commonly available 35 mm film, will introduce more error in the final solution (Fryer et al.: 1990: 18). Photogrammetric transparency film which as been specially manufactured to minimize the effects of shrinking or expansion due to processing and storage, can experience changes up to 0.2 percent of their area (Wolf, 1983:100). These minor deformations are corrected during the photo interior orientation. For non-photogrammetric films, the variation in dimension will be much more (Fryer et al.: 1990: 18).

It is obvious that, from a photogrammetrist viewpoint, using a non-metric camera introduces numerous sources of error which are extremely difficult to control. Fryer and Mitchell determined that if the radial distortion remains uncorrected, the accuracies obtained will be lower than 1 to 200 units (Fryer and Mitchell, 1987: 137 in Fryer, 1992: 17). This would translate to an error of at least 1 centimeter for a photographed surface of 2 meter, or 1 millimeter for an area of 20 centimeters. Though this amount of error is large for most photogrammetric applications, it would be more than adequate for the purpose of recording most archaeological artifacts. However, factors such as the instability of film, the use of film corners rather than pre-measured fiducials and the difficulty to locate them can only contribute to lower the expected accuracies even more. Several methods to control these errors have been tested.

One solution is to use a different transformation to perform the interior orientation. Indeed, photographs taken with a metric camera are usually processed using an affine transformation, which uses independent corrections to fit the x and y axes of the photos to the fiducials. In the case of a non-metric camera, Fryer recommends the conformal transformation (1992: *598).* The latter applies the same correction to both axes and was shown to produce better results. Fryer’s theory is that since there is no control on film flatness or stability, forcing the same correction on both axes produces better results than when different corrections are used.

Others have tried to compensate for the lack of a fiducial plate. Warner and Carson tested two procedures, one consisted of etching marks on the edges of the fixed frame, the other by etching a groove in the camera rollers (1991). The former experiment proved better, with an average accuracy of seven micrometers (versus fifteen) since the rollers are not stable and tend to shift both horizontally and vertically. The use of a réseau plate achieves the same purpose. It is a glass plate with etched cross-hairs distributed over the focal plane area which are imprinted on the film. These points can serve the purpose of fiducials. Moreover they have the added advantage of providing a denser and better distributed set of points with which the computer can generate a transformation taking into account distortions found all over the image rather than only at the fiducial locations.

In the last few years, non-metric cameras have been used in a number of settings where previously metric cameras would have been the only option. B.A. King (1991) used large-format non-metric cameras to document an accident scene and analyzed his results on a micro-photogrammetric workstation. Faig et al. (1992) designed a low cost, non-metric system to evaluate automobile damage. Their method involves two standard fixed-lens 35 mm cameras placed on an 80 cm long rail attached to a tripod and a set of three pre-calculated base distances. The fixed focal length and the pre-determined base distance simplify the generation of good stereo pairs. In order to control the camera interior orientation, he introduced a brass fiducial plate. Although a simple one, this method proved accurate enough and comparable to manual measurements. At the same time it provides a permanent record of the damage. Most importantly it does not require the intervention of a photogrammetrist.

Prior to analytical plotters and softcopy photogrammetric workstations, the field of photogrammetry depended completely on the quality of metric cameras lenses. Optical laboratory calibration could be performed but it required up to a million dollars in equipment (Fryer, 1989:62). Computers now make it possible to take into account the characteristics of a specific camera while computing a solution, providing better results when using metric cameras and allowing the usage of non-metric cameras for applications requiring moderate accuracy.

OVERVIEW OF THE PROCESS UTILIZED

The methods used in this study are basically ones of photographing stereo pairs of artifacts, scanning those images into a digital format and, through the use of photogrammetric software, creating three-dimensional softcopy images from which measurements can be taken. In order to obtain reliable 3-D measurements, the object must be photographed within a known 3-D reference system (or control field). Furthermore, the accuracy of the measurements derived from this system is directly related to the accuracy of the control field surrounding the photographed artifacts. The more accurate the 3-D control field, the more accurate the measured results. Since most artifact collections consist primarily of large quantities of relatively small objects, frames with clearly placed control points of known coordinates on which artifacts are placed are viewed to be most efficient.

Also, very important to this process is image quality, as it will determine the amount of information which can later be extracted through photogrammetry. Image quality can often be improved with simple pre-planning of information needs, object preparation, good photographic equipment and lighting considerations. The following will briefly discuss the methods utilized during this research and will deal with some concerns of control fields, artifact preparation, object orientation and the important aspect of documentation.

Working on a softcopy photogrammetry workstation

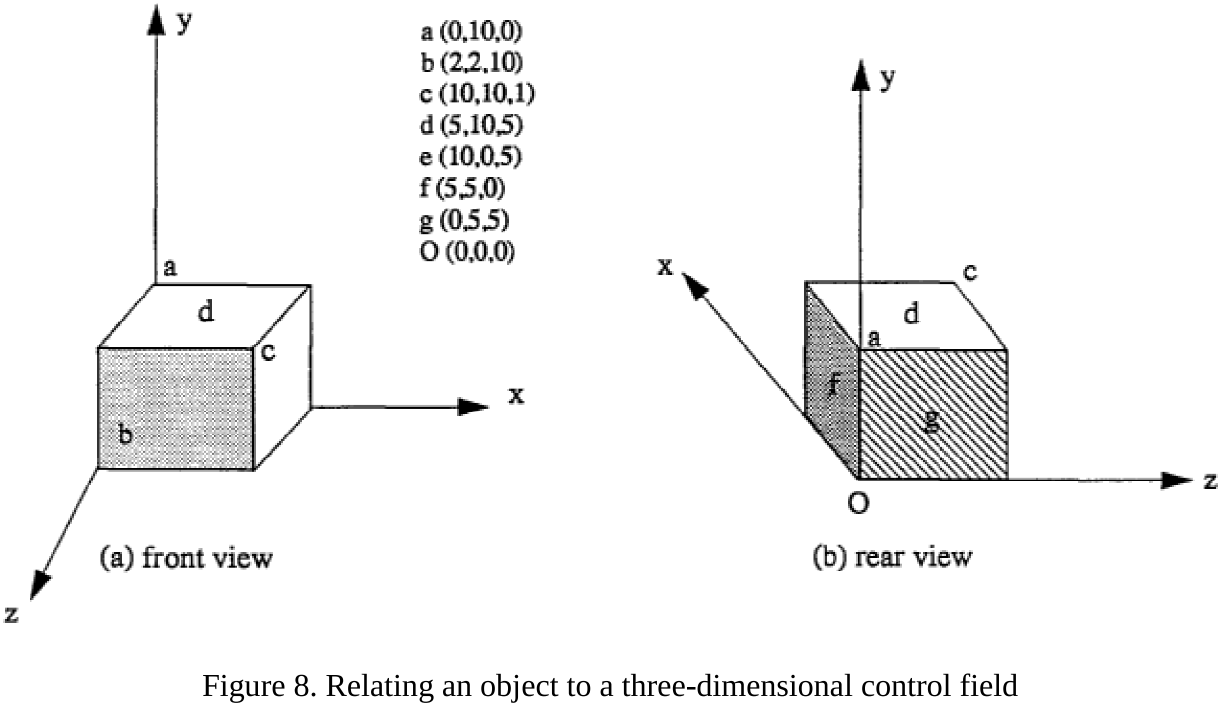
An important aspect in understanding this process is one’s familiarization with the basic operation of a softcopy photogrammetry workstation and the terminology which will be used in the following section. Full-blown systems come with a high-resolution graphic computer screen on which the stereo images can be processed and displayed. The stereo model can be viewed when the orientation process is completed. It consists of the two photos clipped to show only the area of overlap. The display can be put in stereo mode, which means that the user can realistically view the area photographed in three dimensions. Systems with large amounts of memory and a microprocessor dedicated to image display allow the user to fly over the area in real-time (see figure 7). In other words, in the case of an aerial stereo pair, the user is able to move about the image, going down into valleys and landing on and measuring the height of mountains and other features. This action will be referred to as “roaming” in the remainder of the report. Just like on a regular computer, a pointing device or mouse is used to move about the image. Most photogrammetric systems use a more complex device, a hybrid between a digitizing device and a mouse. It allows regular planar displacement as well as movements along only one axis at a time, such as depth (z), width (x), and length (y). The movement of the cursor is displayed in real-time and given with respect to the ground or real life coordinate system of the model. The user viewing in stereo experiences a realistic sense of depth and quickly learns to rest the cursor on a feature

Figure 7. The ImageStation softcopy photogrammetry workstation

while the three-dimensional position of the cursor is automatically displayed by the software, providing, for example, the user with an accurate reading of an object's depth. This capability is used to model surfaces and generate DEMs. Other very powerful functions of these systems are that of taking measurements three-dimensionally and digitizing features, e.g. artifact outlines, the rim of a pot, or a river. Being able to see artifacts three-dimensionally and in color could be an invaluable advantage to archaeologists, especially since these images could provide a record of artifacts which could be shared with or distributed to every organization requiring information of said artifacts without having to move the objects themselves.

A. THREE-DIMENSIONAL CONTROL FIELD

To obtain reliable three-dimensional measurements, artifacts being studied must first be related to a known three-dimensional reference system or control field. This allows any points within the image to be mapped to a unique set of coordinates with respect to a single origin (see figure 8). The accuracy of the control field is extremely important and is directly related to that of the measurements which can be retrieved from a stereo pair. Our target is sub-millimeter accuracy for small artifacts and somewhat less for larger ones.



(a) front view

(b) rear view

Figure 8. Relating an object to a three-dimensional control field

One method of defining a control field is to select an origin on the object to be photographed as well as six or more other points all visible to the camera and to derive for each of them the x, y, and z coordinates with respect to the chosen origin. These points win serve as controls for the absolute orientation process. Points a through g on figure 8, for instance, would not all qualify as controls since f and g are located on the back of the cube, and would not be visible to the camera.

We have briefly experimented with this method in order to assess the speed, efficiency and quality of the results. Our object was a rectangular plastic case on which targets or labeled stickers were placed to identify the controls. The x, y, and z coordinates of each point were measured manually. The task of gathering control points creates several problems. First, since it is directly dependent on the object photographed, it would have to be performed for each and every -object, which would defeat the purpose of this study. The other concern is accuracy. It has been stressed earlier that the accuracy of the controls is the single most important condition for the extraction of good measurements. Determining an object’s dimensions is relatively simple, however, relating them to a single origin can be very challenging, especially for circular and irregular shapes. It is also difficult to assess whether an object is as regular as it seems. The plastic case used, for instance, is rectangular in shape, but without specialized equipment it is impossible to assess whether it is slightly warped or not.

A simpler and faster alternative for creating a control field is to place an object of known dimension in the vicinity of the artifact, or better, a structure or frame around it. Control points are selected and measured on the frame itself, creating a self-contained and reusable three dimensional field, and eliminating the need to associate control points with the artifacts themselves. Photogrammetric practice dictates the use of at least five control points, including two three-dimensional points, two vertical and one horizontal (Wolf, 1983: 394). Since we used non-metric cameras, our recommendation is to have at least twelve controls. The software does not require that many, but having more points will increase the number of redundancies and improve the quality of the absolute orientation (AO) solution. Similarly, it gives one the opportunity to select only those contributing to good results and decreases the chances that an important control could be blocked out by the artifact. The placement of controls has a direct impact on the quality of the AO solution. If artifacts are photographed individually, controls should be located so as to surround the object in both planar and vertical directions. In other words, control points should be placed all around the object, and their height should vary to fully span the extents of the object photographed.

While there are many different types of potential control frames, we will discuss here only the design and results of those built and tested during this research. Commercial control fields are also available. In general the fields can be divided in two types: those suitable for horizontal photography and those for vertical photography.

1. Control frames for horizontal photographs

The simplest type of control frame that we utilized is merely an open cube constructed of 1/4” square basswood strips, the type that is used in model or kite making (see figure 9). Wood was used despite its known sensitivity to humidity, primarily to test the usefulness of a cubic frame. Cross hair targets were applied and measured as accurately as possible with a ruler. Care was taken to try to insure that the corners were kept to 90 degrees. The resulting frame, however, was not always perfectly 90 degrees and this undoubtedly introduced some error. We believe that cubic control frames have some merit, but there are problems. On the plus side, a frame of this nature is fairly easy to construct and to place around an artifact. The problems are varied; for example, there -can be complications with the visibility of the control points if care is not taken in the shift of exposure stations. In most cases, the bars in the front of the control frame block the control points mounted on the back bars (note the back right hand corner of figure **9).** With this particular setup there are also problems in calculating the depth or thickness of an object, as it can be difficult to place the artifact at a known distance from the back plane of the frame. It is impossible to measure the depth of an object from the imagery unless the position of the artifact with respect to the back plane has been recorded at the time the stereo pair was shot. Another minor problem with this type of frame is that the control frame can obscure the very bottom of the artifact. This, however, can be easily corrected by placing the object on a pedestal.

Another frame design we experimented with can be described as an open sided box (see figures 10, 11 and 12). The sides were placed at a 60 degree angle to insure visibility of all control points during stereo pair photography. This frame was constructed of approximately 3 mm thick Plexiglass and was etched with a 1 by 1 cm grid to insure that enough control points would be visible even if many were obscured by the object being photographed. Some grid crosses were filled with a black filling, backed with white paper, and letters were attached to insure that they would be visible and that one could orient oneself while locating control points on the scanned images.
This system was superior to the cube in every aspect except, of course, the ease of manufacture. Being transparent, Plexiglass enabled us to minimize the effect of shadow by lighting the object through the back plane. Another problem with this frame was that the Plexiglass tends to reflect in places which obscures some of the control points, however, this can be corrected with lighting or frosting the Plexiglass. Frames designed for horizontal shooting presented several problems, for one, it is hard to insure that objects were truly against the back (or zero depth value) of the control frame (see figures 10 and 12). In order to do this, the object must have a bottom or base that allows it to sit flush with the back of the control frame, and that is not likely. Moreover, to measure accurate depth of small artifacts, like projectiles and other lithic tools, these must be attached to the back of the control frame with an adhesive, and that is not desirable in most cases. In theory, we believe this to be a good control design, but due to its fairly complex manufacture

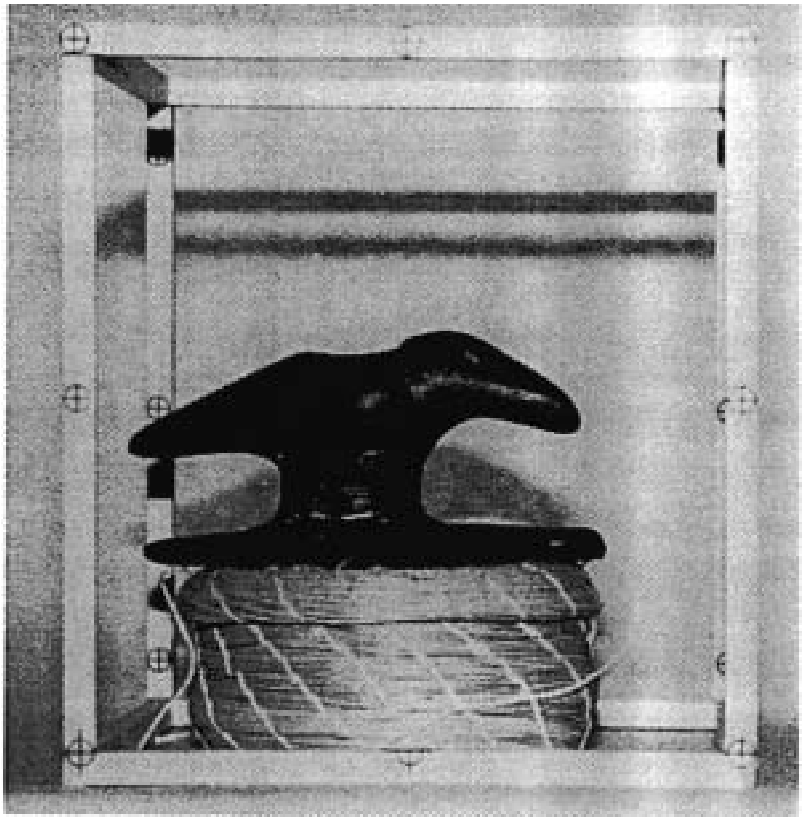


Figure 9. A cubic horizontal frame

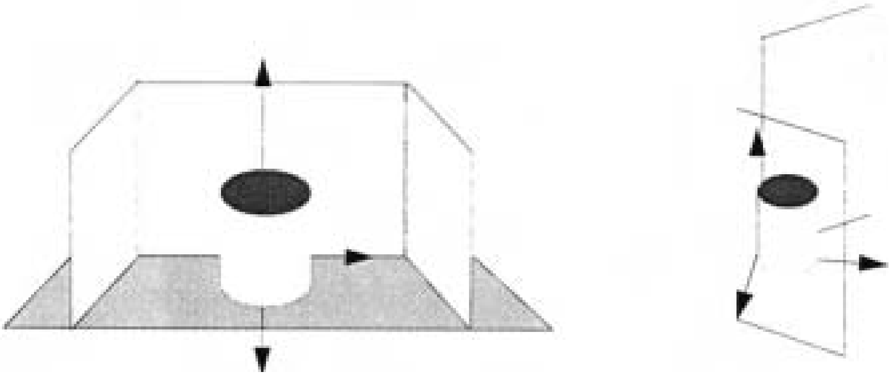


Figure 10. Placing an object within a horizontal frame

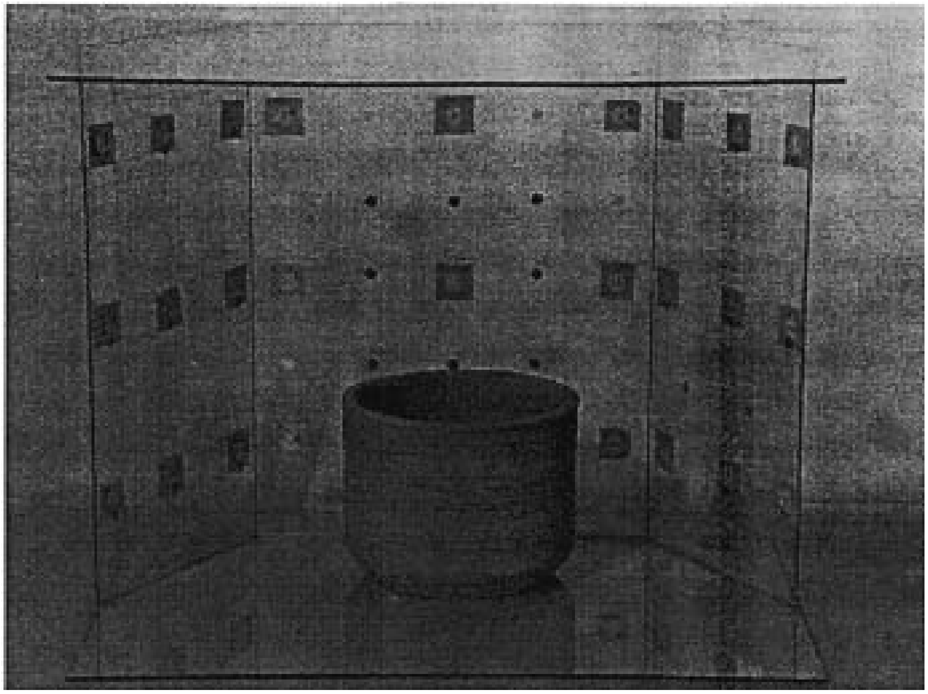


Figure 11. A Plexiglass frame front view

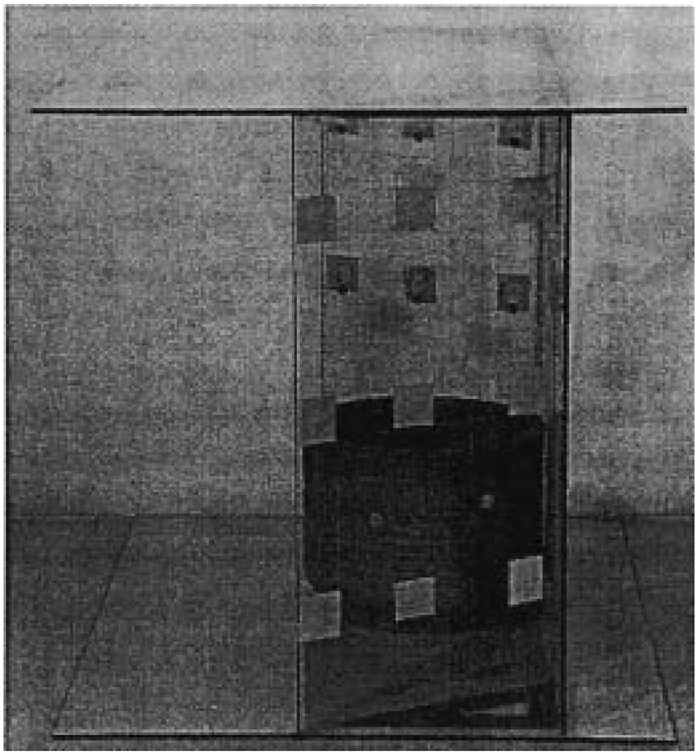


Figure 12. A Plexiglass frame side view

and lack of stability, partially due to our choice of a thin material, we decided to experiment with some control systems suited for vertical shooting.

2. Control frames for vertical photographs

The purpose of going to a vertical type design was two-fold. Firstly, this design allows for the artifacts to simply be placed on the control frame with the assurance that they are resting against the back plane (or zero z value). Secondly, it was designed with the idea of quickly processing numerous small artifacts. The control was constructed of common 1/4" glass plate, which was tested for flatness at a machine shop and proved to be flat within 2/1000" (0.05mm). The glass was lightly frosted with flat white paint and a grid was carefully etched to control for x and y. The z controls consist of the glass plate itself, being the zero value, and of several blocks of known height which were placed at a known x and y coordinate locations. This system proved to be the most accurate that we tried as well as the easiest to build and utilize (see figure 13). As with the Plexiglass frame, a translucid material was selected so the artifacts could be lit though the back plane in order to reduce shadow. Glass also has the advantage of being a very stable material which will not warp with the heat of lights, and which can withstand a fair amount of weight without bending. The glass should be frosted on the face that will be exposed to the camera, as this will allow easier landing on the zero z value during the softcopy measuring. In other words, if the grid is etched on the side opposite to the camera, one would have to "drive" the cursor through the glass in order to land on the grid, or zero depth value. Hence, the software will assume that depth 0 is 1/4" below the artifacts and all measurements would have to be adjusted manually. This might also introduce error, as the plate glass is not of optic quality and will likely bend the light. For ease of choosing the proper points and orienting oneself while in stereo-viewing, it is very important that control points be marked with cross hair targets and clearly labeled on the grid.

For this type of control field, the x and y measurements gave results that were quite acceptable, with depth measurements being somewhat less accurate. There are likely several sources of introduced error which affect the accuracy of the depth (z value) results. The questions of how to deal with these introduced errors will have to be answered at a later date. However, the accuracy of the results from this type of control frame, to be discussed later, does prove the ability of utilizing such a system.

Following the same design principle, we constructed a much smaller version of the flat glass control field (figure 14), designed for high accuracy measurement of very small artifacts (i.e. beads, small projectiles, etc). This glass product is commercially produced through a photo-mask process and measures 10X10 cm. It contains a very precise iron oxide grid sandwiched between two thin plates of glass. While this glass is too thin to support much weight, it can be placed upon

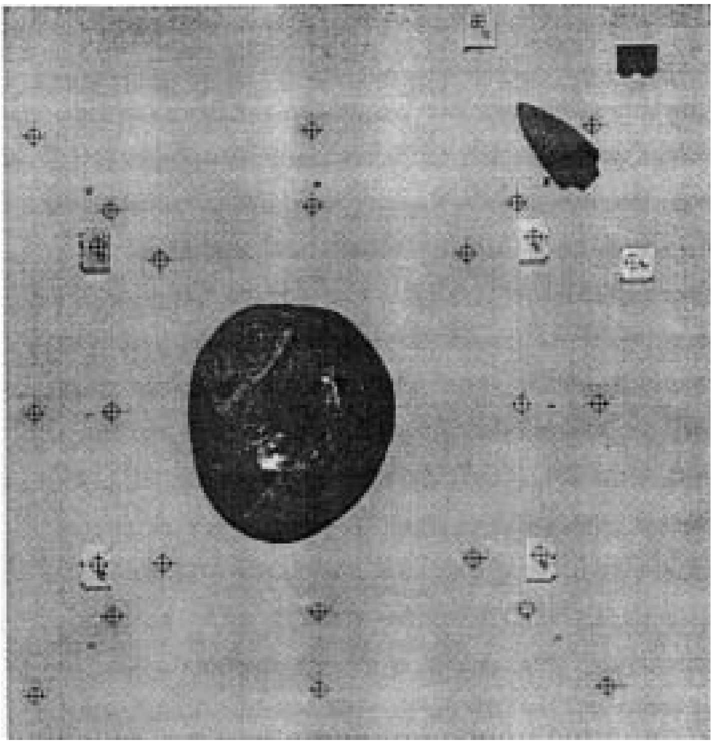


Figure 13. Using a standard glass plate as a simple vertical frame

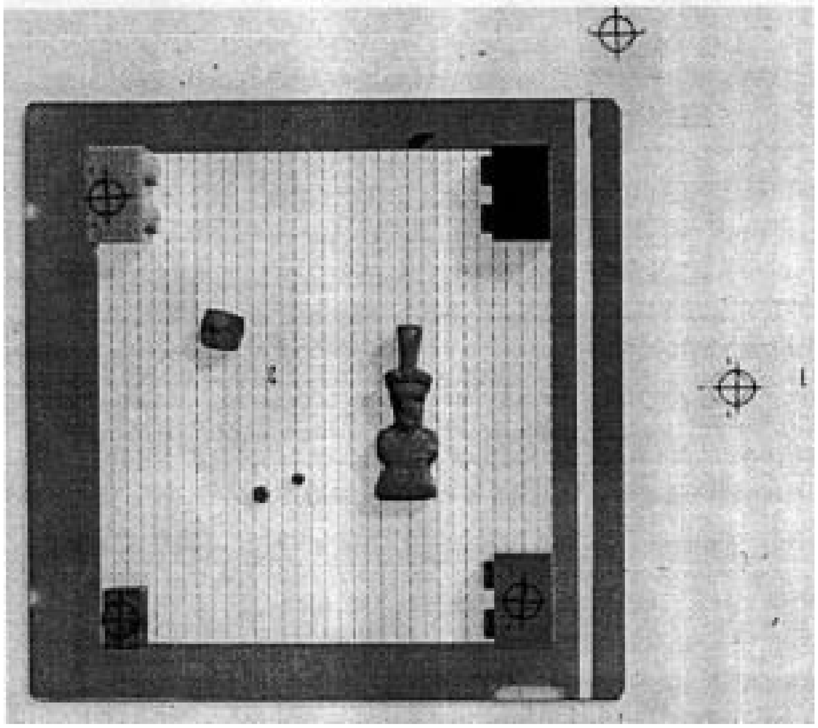


Figure 14. A 10x 10 cm vertical control frame

a more sturdy (1/4") glass frame and still allow backlighting. This control frame resulted in very low error and worked well for small objects. We are involved in trying to establish what kinds of grids are available from different manufacturers and what the costs of acquiring these grids would be, hence saving individual manufacture time and effort.

To simplify the process and reduce the number of control frames needed for different sizes of objects, we etched a paint frosted glass plate with two grid sizes (see figures 13 and 15). This allows the same control field to be used for both small and medium sized artifacts. The smaller artifacts would require smaller depth controls placed around them at known positions. Pyramid-like controls were also designed to offer a continuous range of depth values which could be selected to suit that of the artifact archived (see figure 16). In this case, one would use the bottom row or two for objects that did not have a lot of depth, and some of the upper rows for those that had a greater z value. These stair-like controls were machined from thick Plexiglass stock.

The control frames presented here target small to medium artifacts. To take good usable photographs it is best to have control points located closely around or on the object itself. A major inconvenience is that a different frame is necessary every time the object size changes greatly. For those archaeologists or museologists specializing in one type of material such as lithics, beads or pots, a single frame will do. For others, a set of frames might be necessary. Table 1 suggests basic guidelines in order to design control fields which could be used with the appropriate artifact type and size.

Table 1: Suggestions of frame orientation and size depending on the artifact type

Artifact	Artifact	Frame	Frame
Type	Size	Horiz. / Vert	Size
Beads (one or more)	**1 - 5 mm**	**Vert.**	**l0xl0cm**
Small tools (several)	**5 mm - 3 cm**	**Vert.**	**30x30cm**
Medium tools	**3 cm - 15 cm**	**Vert.**	**30x30cm**
Medium objects	**10 cm - 40 cm**	**Horiz.**	**40x50cm**

Large to very large objects have not been dealt with during our study, due primarily to time constraints. We, however, offer a design for an adjustable control frame which could be built to be as low as 50 cm or as high as 150 cm. This design has the following advantages: side-panels which can be slid outwardly to fit narrow and wide objects, two vertical bars in the front and the

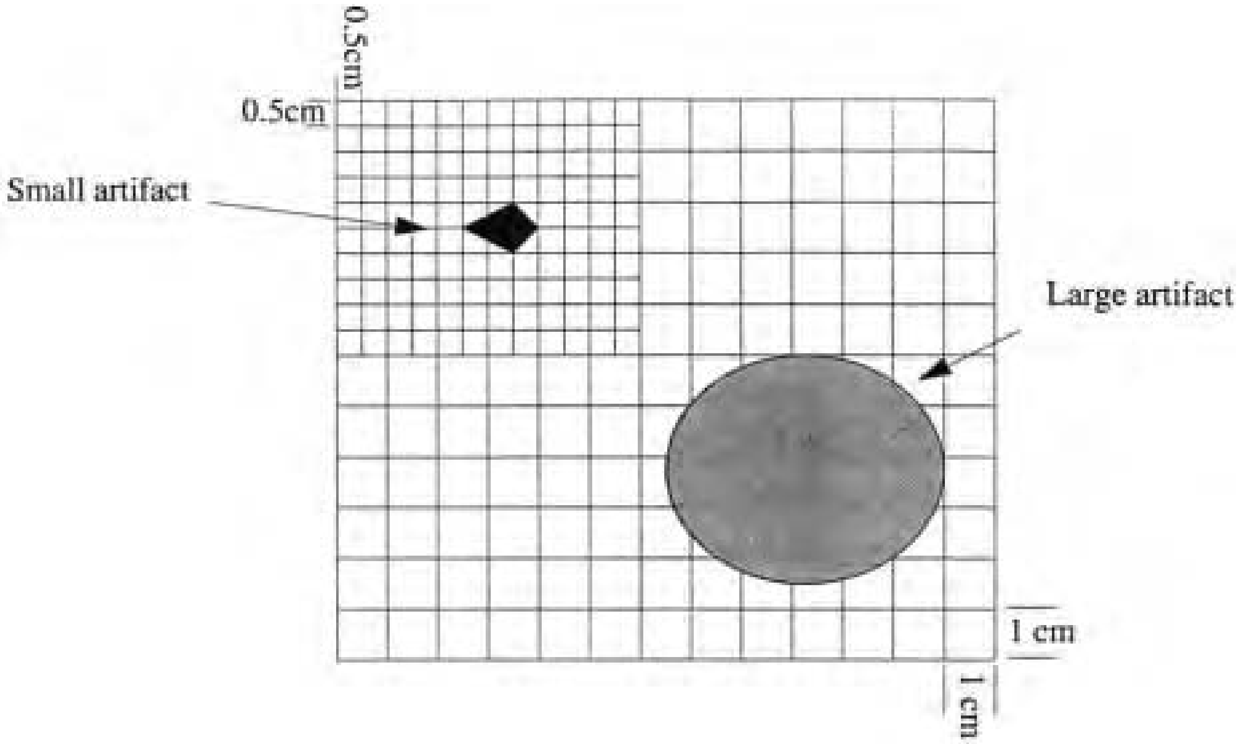


Figure 15. Two grid systems within one vertical control frame

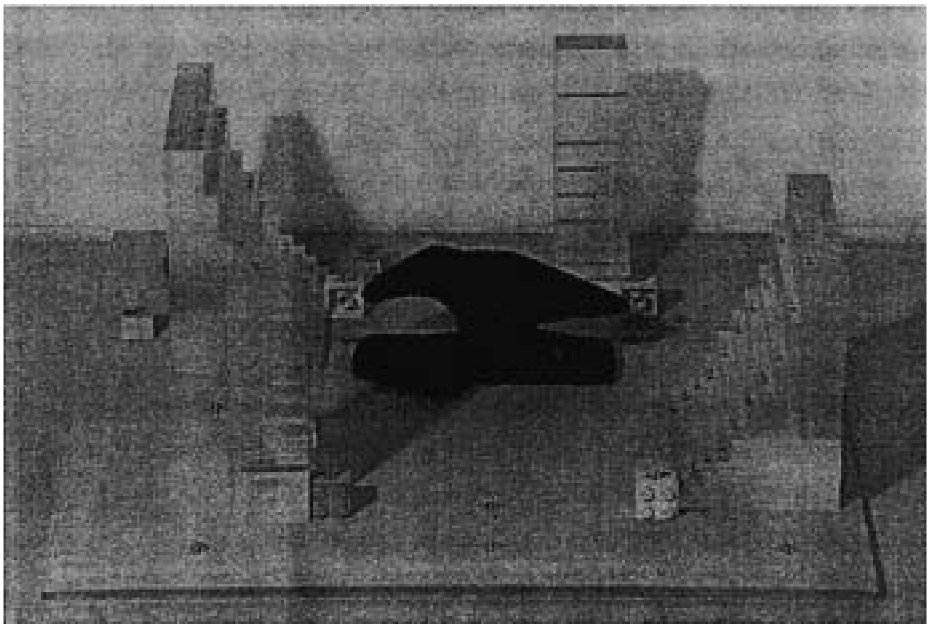


Figure 16. Using pyramid-shaped blocks as vertical controls

back which can be slid up or down, insuring an object would be surrounded by control points on all sides no matter its height. The angled side-panels are considered necessary since they reduce the risk of control point blockage (see figure 17).

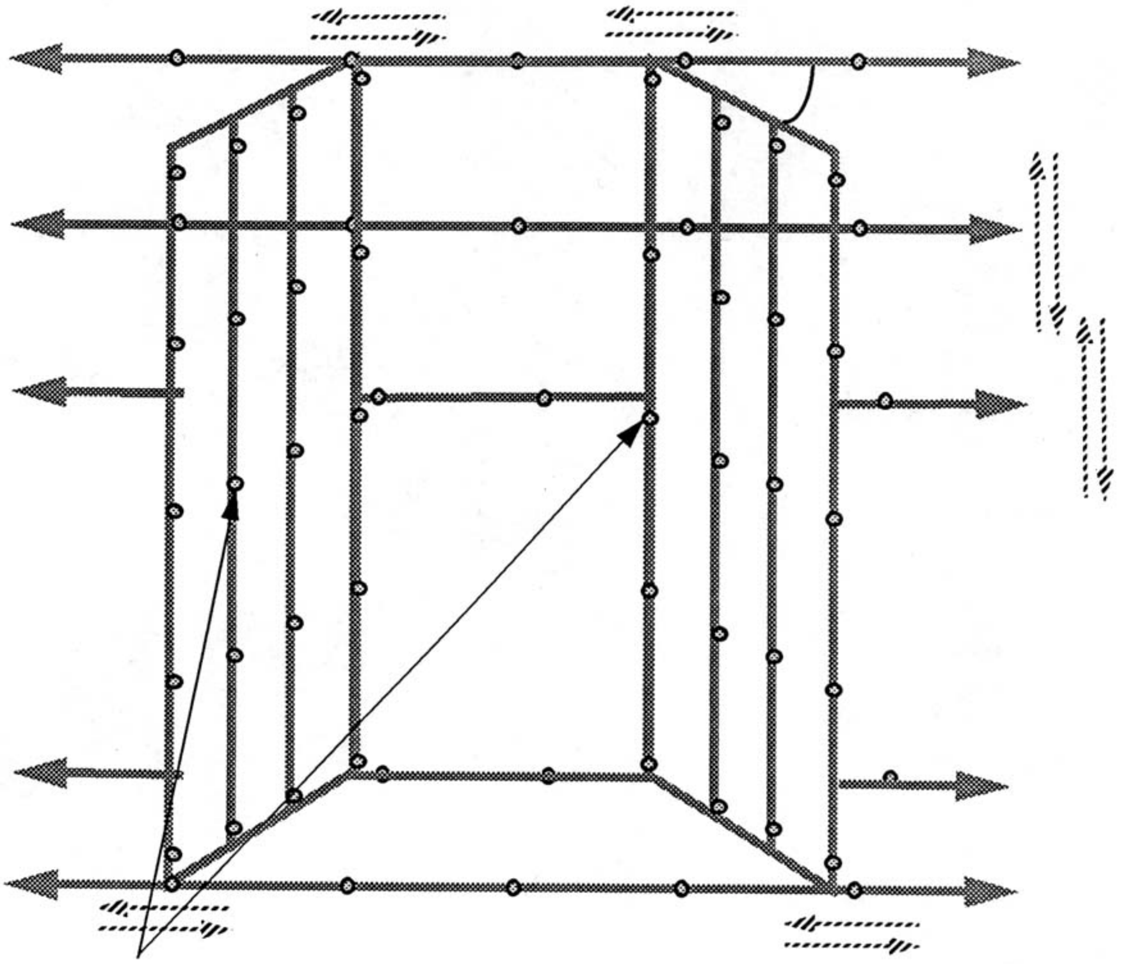
B. ARTIFACT PREPARATION

Artifact preparation for photographing stereo pairs is an important step, and careful consideration should be given to methodology. One must think about not only the diverse physical nature of the cultural materials but also about how to best preserve information and help to answer - the diverse research questions that might be asked of the collection in the future. The obvious metric data such as the lengths, widths and thicknesses of the artifacts, while very important, might not be the only consideration when deciding from which and from how many angles an artifact should be photographed. One should think about what sorts of information, researchers might ask of a collection and how it can be best recorded photographically. This is especially important in cases where artifacts will not be available for study in the future. Harp points out that "... no effort of cost should be spared in the interest of making this illustrated record complete" (1975:11).

Throughout the experimental research involved with this project, we have been conscious of the wide variety of physical materials that make up the archaeological record. While we have not photographed or studied all materials, we did try to include a diverse assortment (i.e. pottery, a variety of lithics, bone, metal and glass). This wide range of material not only produces problems for the photographer when trying to extract the pertinent information for good image quality but can also present problems when attempting to take measurements in a softcopy situation. Proper photographic procedures, such as lighting needs for various surfaces, have already been thoroughly dealt with in numerous photography manuals, so we will focus here only on the photographic problems encountered when trying to measure objects from photographs. However, when dealing with photographic images, especially those that are designed to preserve the archaeological record, there is no substitute for good photographic technique.

1. Shadow

In any photographic effort the central question must focus on what is the purpose or goal of recording the object. For example, are there small incised or otherwise applied features, or should interest be focused on the overall shape and size of the object? While it would be optimal to record all possible aspects, this is not always feasible due to costs or time constraints. When trying to measure an object from a softcopy model, the artifact edges must be clear and not blended with shadow. If it is not possible to view the edge of an object accurately, then no accurate



Possible
locations of control points

Figure 17. A suggested design for an adjustable horizontal control frame

measurements can be extracted. While the software that we used for this research does have the ability to control for image contrast and balancing, it is highly recommended that problems be resolved as much as possible before taking the photographs. Good photographic technique cannot be over emphasized, even when using the best hardware and software available. This research has utilized several different methods of illumination, but a three light system that allows one lamp to be used for a backlight appears to be the best for most purposes. Proper lighting will effectively cut down on artifact edge distortion, which will allow for easier and more accurate artifact measurement. Shadow is more important to consider when one is shooting a dark object than a light surfaced one. With a light colored object it is possible to pick out the edge of the object quite clearly but this is not easy with an object that is dark in nature. Some shadow is desirable when trying to show object texture, inscriptions, etc.

2. Object Texture

Object texture is not only of concern when considering lighting and achieving detailed photographs but can also be a problem for softcopy three-dimensional measuring. This does not present a problem for planar measuring (x and y). However, when trying to properly locate the cursor in the z axis, it can become difficult to determine when it has actually landed on the object's surface. Problems are more likely to occur when dealing with relatively smooth surfaces with no color contrast. It may be possible to apply cross hair targets directly to the object in such situations. With these clear targets the software operator has locations with strong contrast on the object surface resulting in more accurate measurements. There is the issue of application of an adhesive to an object's surface. It is important to weigh the value of more accurate measurements against possible surface damage to the artifact. This should not be of great concern in most cases if care is taken in applying and removing the cross hair targets. A simple, low cost method is to utilize cartographic registration marks, which come in a roll, much like scotch tape. Clear or aqua glass artifacts have also presented some measuring problems in the z value. Generally, they can be handled in a similar manner with little concern for damage to the artifact. Metal artifacts with a smooth surface are also problematic, and the problem is magnified for dark colored objects. Objects with horizontal texture can also be hard to measure in the z axis (see figure 18). The software focuses the image for a specific z value by moving the images horizontally. If the object has parallel horizontal lines, it is very difficult for the human eye to determine when they are correctly matched. This problem can be solved with the application of cross hair targets or, in some cases, by orienting the object in a different position prior to shooting the stereo pairs so that the texture is no longer horizontal.

Baskets, with their textured surfaces, are relatively easy to deal with, as are most lithics

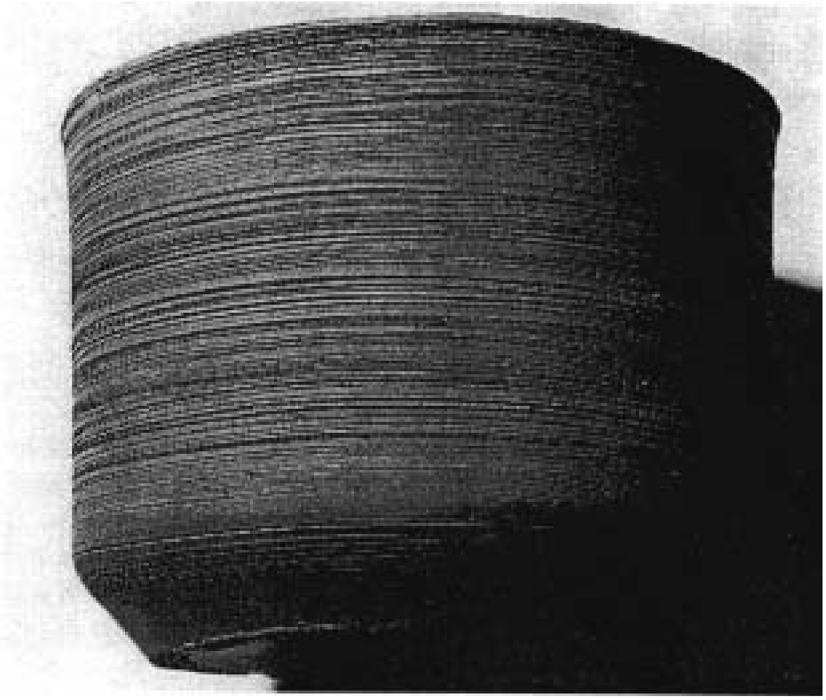


Figure 18. An example of horizontal texture

since they usually have some texture from reduction or sharpening scars. Measurement in the z axis varies for bone depending on its texture and surface features.

In summary, if an object has very little surface texture, cross hair targets should be considered if the object will not be damaged; these targets will greatly aid in Z value measurement. The targets should be applied at locations that are not in the same plane so that different z values can be measured. Figure 19 gives a simple example of where cross-hair targets might possibly applied.

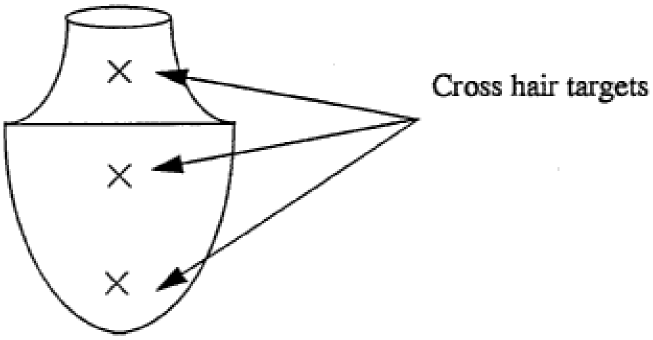


Figure 19. Placing cross hair targets

3. Object Orientation

In dealing with object orientation, one must not only consider where the artifact is in space, but also what features or aspects should be preserved in the images. If dealing with relatively small stone objects, the choices of view are somewhat limited and fairly obvious. A ceramic vessel, in contrast, with its various decorations, overall shape, orifice size/shape, etc. presents a richer set of challenges. It may be necessary to position the object in a number of different orientations so that all areas are photographed. The number of images may also be affected by the size and extent of detail on the object. For larger items it may be necessary to structure images that show the entire item as well as close-ups of particularly significant details.

Decisions such as these need to be considered before bringing artifacts to the studio. If there is a large collection to be recorded, a well thought out, methodical, assembly-line type of process will save time and money and will provide a better record of the material for future analysis.

4. Documentation

As in all photographic collections, careful records should be kept that describe the object(s) of interest. Each image should show the appropriate artifact label, e.g. site and accession numbers. This is particularly true when a single item is photographed from a number of different vantage points. It is essential that the various views be properly associated with the same item.

Along with the documentation records, care must be taken that control frame information is linked with the photographs since the control frame values will be necessary for future use with the photogrammetry software. Other information about the photography setup should also be kept with each pair or film strip. A form, designed as a comprehensive shooting record, is attached as part of this report’s appendix. It allows all of the pertinent information to be easily recorded during a shoot, and it can then easily be filed with the original photographs.

In dealing with control frame documentation, each control point utilized on every frame should be clearly labeled, and these labels should be clear in the photographs. In order to label the points on control frames, it is possible to use small rub-on lettering. This allows users in the future to accurately associate and identify the proper control points with the correct three-dimensional control coordinates. One method of dealing with this is to simply use a table to keep the information together (see table 2). This table lists the control frame identifier, the control point labels, and the three-dimensional coordinates (with units) that correspond to each label point. This information should also be kept with the appropriate photo strips.

Table 2: Example of Control Point Record

Frame Identifier	Control Point Label	x Coordinate (units)	y Coordinate (units)	z Coordinate (units)
Horiz. #1	**Al**	**0**	**0**	**0**
Horiz. #1	**A2**	**1.50**	**5.00**	**0**
Horiz. #1	**A3**	**5.00**	**5.00**	**0**
Horiz. #1	**A4**	**5.00**	**0**	**0**
Horiz. #1	**A5**	**10.00**	**-5.00**	**10.00**
Horiz. #1	**B1**	**10.00**	**0**	**10.00**
Horiz. #1	**B2**	**-5.00**	**10.00**	**5.00**
Horiz. #1	**B3**	**-10.00**	**-10.00**	**5.00**
Horiz. #1	**B4**	**-5.00**	**-10.00**	**5.00**
Horiz. #1	**B5**	**-10.00**	**10.00**	**5.00**

If an institution has a collection of numerous small artifacts, we recommend that they are shot in groups, as long as proper identifying labels are included in the shot. As this project is designed with economy of both time and money in mind, we tried to look at the practical aspects of shooting a collection along with the ability to accurately retrieve metric data. It is our opinion that numerous small artifacts can be shot together and still retain accuracy as well as record the necessary information. However, if there are artifacts from more than one provenience, they must be clearly labeled for the record. Also, if both sides of the artifacts are to be photographed, care should be taken that they stay with their respective labels. If shooting a group of artifacts, one needs to insure that a sufficient number of well distributed control points is clearly visible. In the event -the cross hairs or marks used are not suitable for publication, they can be removed using an image processing software package.

C. PHOTOGRAPHIC EQUIPMENT AND SETUP

1. Camera body

The past decade has seen a dramatic improvement in the quality of standard 35 mm single lens reflex (SLR) camera systems, making them suitable for many close range photogrammetric applications requiring accuracies lower than 1:1000 (Donnelly and Fryer, 1989 in Fyer et al., 1990: 26). The primary advantage of these cameras is their low price. The difference in cost of a 35 mm metric camera and a standard off-the-shelf camera can run into the thousands of dollars. These new low cost alternatives to the metric camera can facilitate research for low-budget applications. Standard 35 mm cameras from most reputable manufacturers are generally considered to be equally suitable as a non-metric cameras since the design is relatively standardized, especially with regards to the film transport mechanism. One would therefore select a camera body based on availability, price, past experience, or the type of attachments available for that camera. There is a potential, however, of considerable variation in lens quality and the lens used should be selected carefully, as discussed below.

For this study two different brands of cameras were tested, a Minolta X700 with a zoom 28—70 mm lens and a Nikon F3 with a Nikkor 55 mm lens.

2. Lenses

To negate the influence of lens aberrations, multiple lenses are usually mounted in different configurations in order to produce sharper images. Modern computer- designed camera lenses are made of at least ten individual pieces. Although very adaptable to general photography, zoom lenses are not recommended for photogrammetric applications since the exact focal length used when taking stereo pairs must be accurately known. Use of lenses with a fixed focal length between 60 and 135 mm will most likely lead to superior results. Because such systems are in common use, we conducted evaluations of a zoom-lens based system. During our testing of the zoom lens, we fixed the focal length at 70 mm in order to relatively control for focal length. For photographing small objects, one would need macro lenses and, for shooting very small artifacts, bellows and close-up kits are necessary. Close-up filters should be avoided due to their inherent distortions. The Nikon camera produced better results with a ten-fold increase in accuracy for z values in some instances. It is reasonable to infer that the higher quality and more simply constructed Nikkor fixed focal-length lens system causes less distortion than a zoom lens system. -However, an in-house calibration should be done and other Nikon cameras tested before this hypothesis can be confirmed. It is possible that lens calibration may allow correction of much the distortions introduced by the zoom lens (see the results section).

3. Film sensitivity, resolving power and longevity

Black and white film is recognized as having an almost unlimited longevity when properly processed and stored. Color film on the other hand, is much more likely to fade. The fact that these images are to be transformed to a digital format to be photogrammetrically processed, may be seen as reducing, somewhat, the requirements for long-term color stability.

The sensitivity or speed of a film is determined by its concentration of various silver halides such as silver bromide, silver chloride, and silver iodide. The sensitivity of a film is indicated by its film speed and coded using the ASA or DIN numbering systems. The ASA numbering is proportional to the film speed and inversely proportional to the film exposure. In other words, doubling the ASA number doubles the film speed but divides the exposure time by two.

The resolution of a film is also predetermined by the way a particular film is made. The resolution of a film is generally finer if the film speed is lower, and coarser if the ratio is higher. The resolution of most black and white films and Fuji color films is expressed in numbers of line per millimeter. Resolution of Kodak color film, on the other hand, is organized using the categories fine (F), very fine (VF) or extremely fine (EF). These descriptive, rather than quantifying phrases, are used to broadly characterize the high resolutions obtained using complicated color composition system.

Choosing a film is a trade-off between resolution and film sensitivity. In the case of archaeological collections, resolution is the primary concern since only static objects are being recorded. The Kodachrome 64 Professional slide film combined with our three-strobe light system produced good slides exhibiting good image contrast and is suitable to be scanned at a 7.5 micrometer resolution. When asked about their highest-resolution films, the technical support personnel at Kodak and Fuji recommended the Ektachrome Lumiere 100X Professional and the Fujichrome Provia 100 Professional respectively. However, there is much complexity in technical procedure of the production of today's color film; some professional films can actually have higher speeds and maintain fine resolution. Each professional film also has other qualities like edge sharpness, color accuracy, and so on, and film selection should be matched to the characteristics of the object, photographer's skill, budget and other similar factors.

The long-term storage and potential for color fading are important concerns. Most unprocessed film must be kept at room temperature and in a low moisture environment. Professional films, however, can have more specific storage condition requirements. Carefully reading and following the instructions will guarantee good results. The quality of a film is at its peak when it is new. The quality tends to gradually degrade with time and a film approaching its expiration date will produce significantly poorer results especially if it has not been kept in proper storage conditions.

Once processed, film should be kept away from light as much as possible, since dyes fade faster in the light than in the dark. Under the best conditions, a film color fading process cannot be completely stopped. It was reported that Kodachrome has the best dark storage dye stability. Fujichrome products are less likely to fade during projection. For a given amount of fading, Fujichrome slides can be projected twice as long as Ektachrome slides (Wilhelm, 1993). The ideal long-term storage conditions are a temperature of - 18° C and a humidity level between 30 and 50%.

4. Camera movement system

At this point, all components required to take stereo images are now ready. A camera, lens, lighting, film type, artifacts, and control frame have been selected. These can now be set up to produce stereo images with a sixty percent overlap.

The general procedure can be described with an example of vertical photographs of small projectiles placed within a control frame. The camera will need to be placed at a certain distance above the objects and aligned with the middle of the control frame. The camera is then shifted left and right from this position to generate the stereo images. The distance between the two camera positions is called base distance (Db). That between the camera and the object is referred as camera distance (Dc). These numbers can be computed as long as the focal length of the lens (Fl) and the control frame width (Wf) are known. However, throughout our testing we realized that there is another important factor that must be considered when calculating these distances, namely, artifact depth. In other words, if one had a relatively high depth (z value) control or artifact placed near the edge of the control frame, it might be cut off or excluded if distance CC' is not wide enough to include the whole width of the frame (see figure 20). In order to compensate for this, a

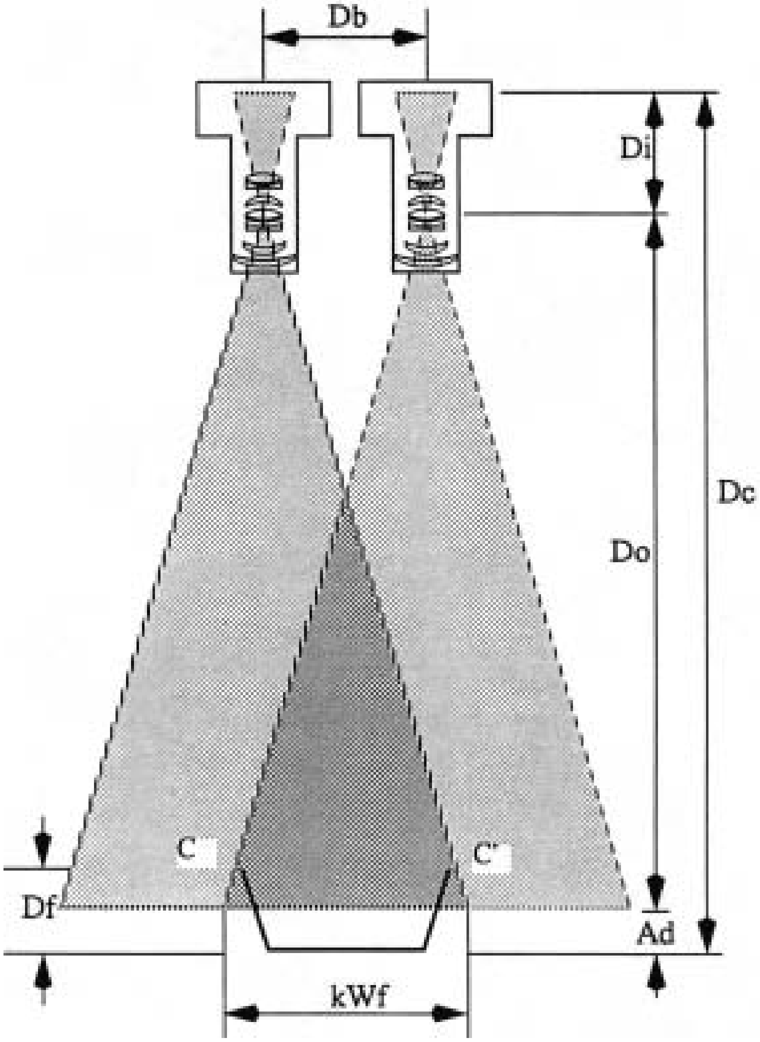


Figure 20. Geometry of the camera setup

variable K was introduced to some of the following equations. This variable, K, basically allows for Wf to be increased by a certain percentage depending upon artifact depth. Two tables have been provided where we list a variety of focal lengths, frame widths, and control or artifact depths (tables 3 and 4). These tables should give the reader a rough idea of how the variable K increases with increasing artifact depth. Also, this table will provide guidelines to yield an adequate overlap for stereo pairs and insure that all of the important information is included in both the left and right images. The guidelines should not, however, take the place of actually carefully looking through the camera viewfinder in order to ascertain that all pertinent information will be included. These tables give the values for the object distance (Do), image distance (Di) and (K) for the corresponding artifact or control frame depths (DO and control frame widths (Wf). The program and formulas used in gathering these figures can be found in the Appendix C. Through the use of the following formulas, one can calculate the camera distance (Dc) and the base distance (Db) or camera movement. While a greater camera distance than those that are listed would also work, here, we are concerned with utilizing as much of the film as possible. In other words, the object(s) of interest will appear larger on the film than they will if a greater camera distance is used than those listed in the tables.

Table 3: Focal Length of 55mm

Depth of Frame (DO mm	Width of frame (Wf) mm	Image Distance (Di) mm	Object Distance (Do) mm	K %
10	**100**	**66.00**	**330.07**	**1.08**
50	**300**	**58.59**	**898.49**	**1.10**
100	**300**	**58.43**	**937.82**	**1.16**
200	**400**	**57.46**	**1287.04**	**1.21**

Table 4: Focal Length of 70mm

Depth of Frame (DO mm	Width of frame (Wf) mm	Image Distance (Di) mm	Object Distance (Do) mm	K %
10	**100**	**84.07**	**418.19**	**1.07**
50	**300**	**74.61**	**1132.84**	**1.09**
100	**300**	**74.45**	**1172.11**	**1.13**
200	**400**	**73.21**	**1594.35**	**1.18**

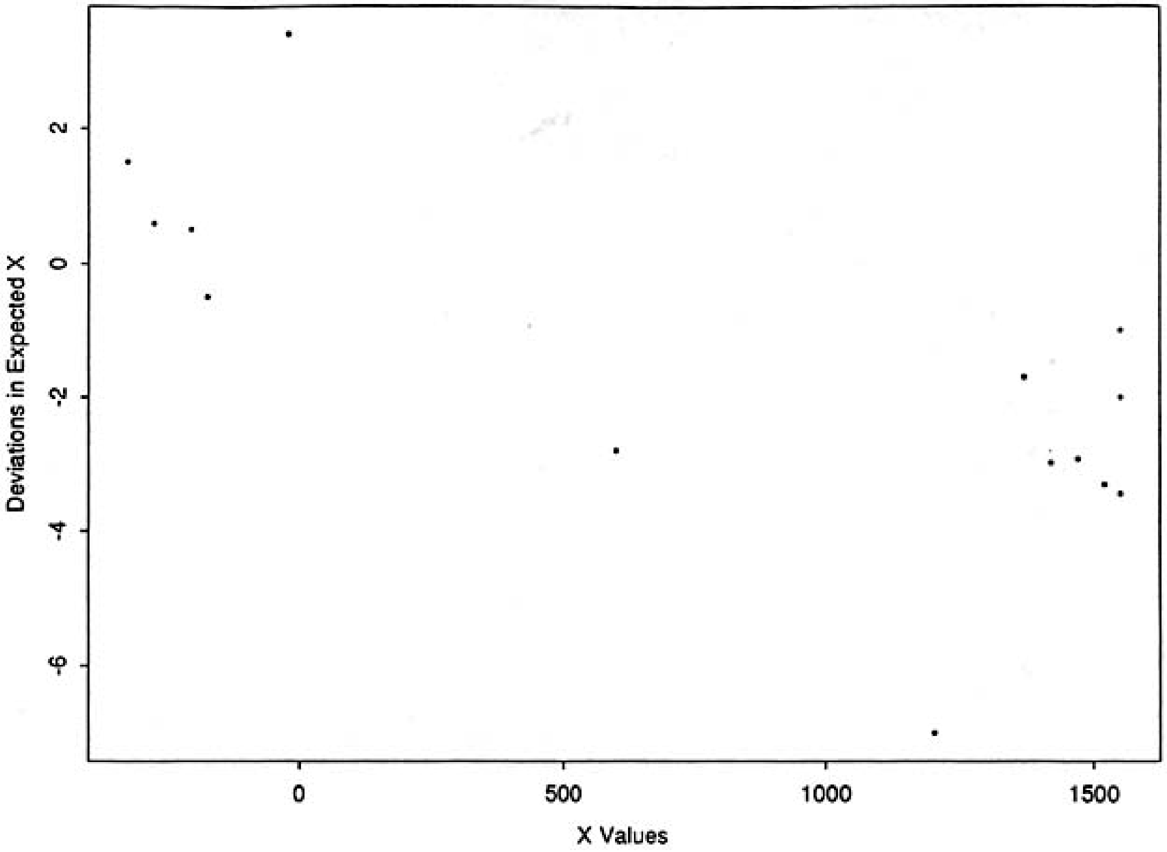


Figure 45. Deviations in x compared to x (Nikon)

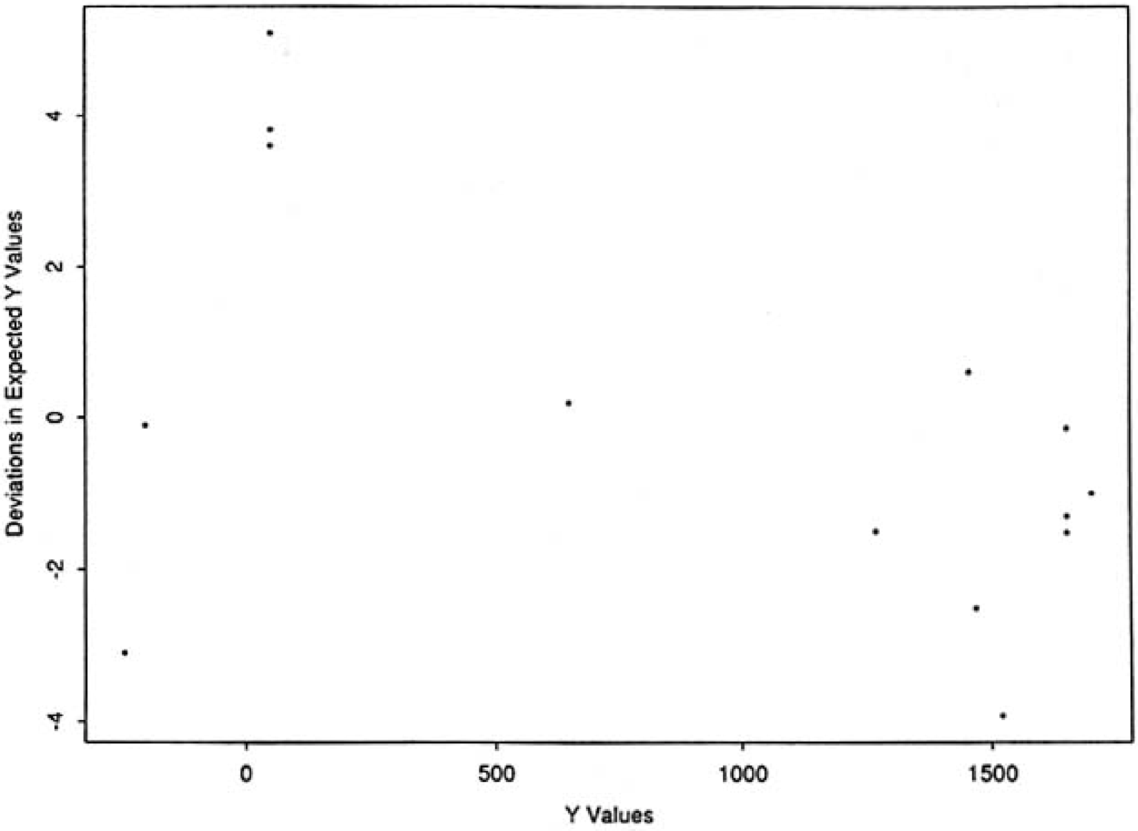


Figure 4b. Deviations in y compared to y (Nikon)

The base distance (Db) and camera distance (Dc) can be calculated from the object distance (Do) and the image distance (Di). Do represents the distance from the center of the lens to the average depth (Ad) of the object. Di is the distance from the center of the lens to the film. They can be obtained using the formulas below where:

$$Do = Fl\left(\frac{Wf}{0.6Fs}K + 1\right)$$

$$Di = Fl\left(\frac{0.6Fs}{Wf}K + 1\right)$$

The base distance and the camera distance can then be computed as follows:

$$Db = Fs\,(1 - 0.6)\,\frac{Do}{Di}$$

$$Dc = Do + Di$$

Once the values for parameters Db and Dc are known, the camera setup can be installed. The one built for this study is a low cost home-made system allowing vertical as well as lateral movements. The camera is moved on a rail to control the base distance (see figures 21 and 22) while the rail itself can be moved up and down to adjust the camera distance (see figure 23).

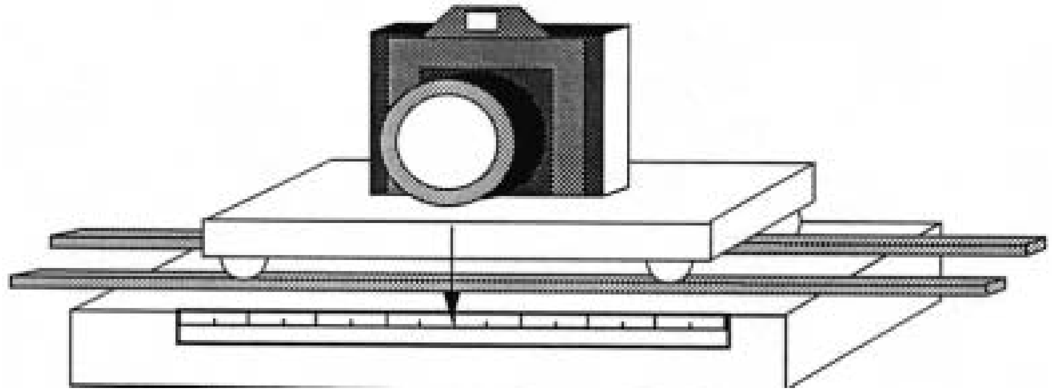


Figure 21. Design for a system to control camera base distance

It is important that the control frame and the camera (or film plane) be relatively parallel to each other. In the case of a vertical shoot, this can be achieved very easily by levelling

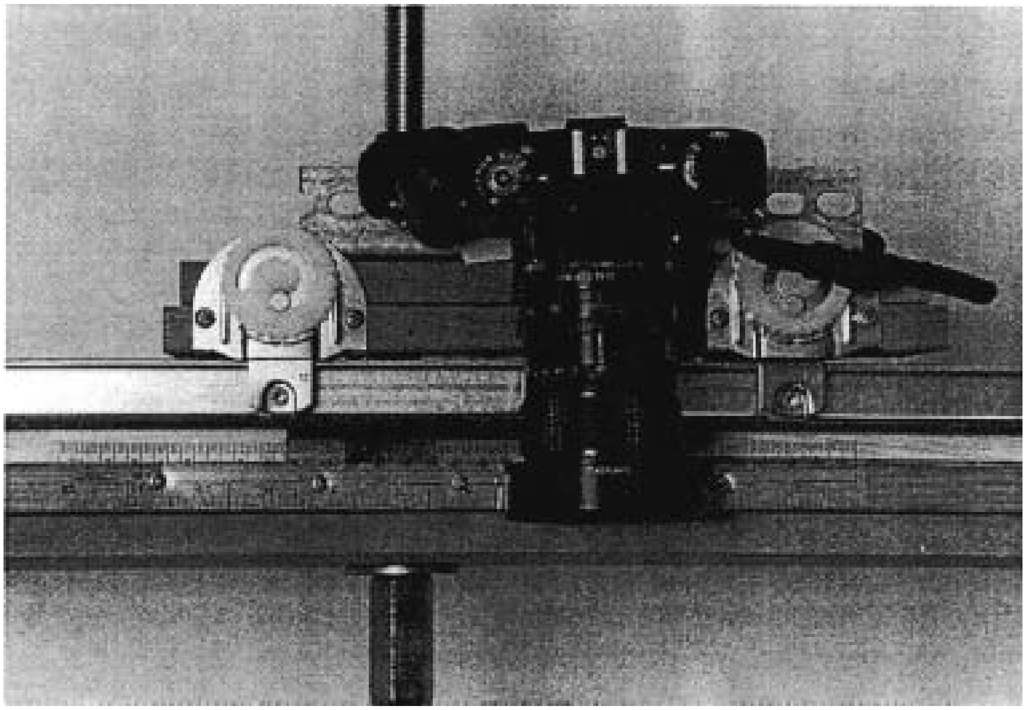


Figure 22. Our system to control for camera base distance

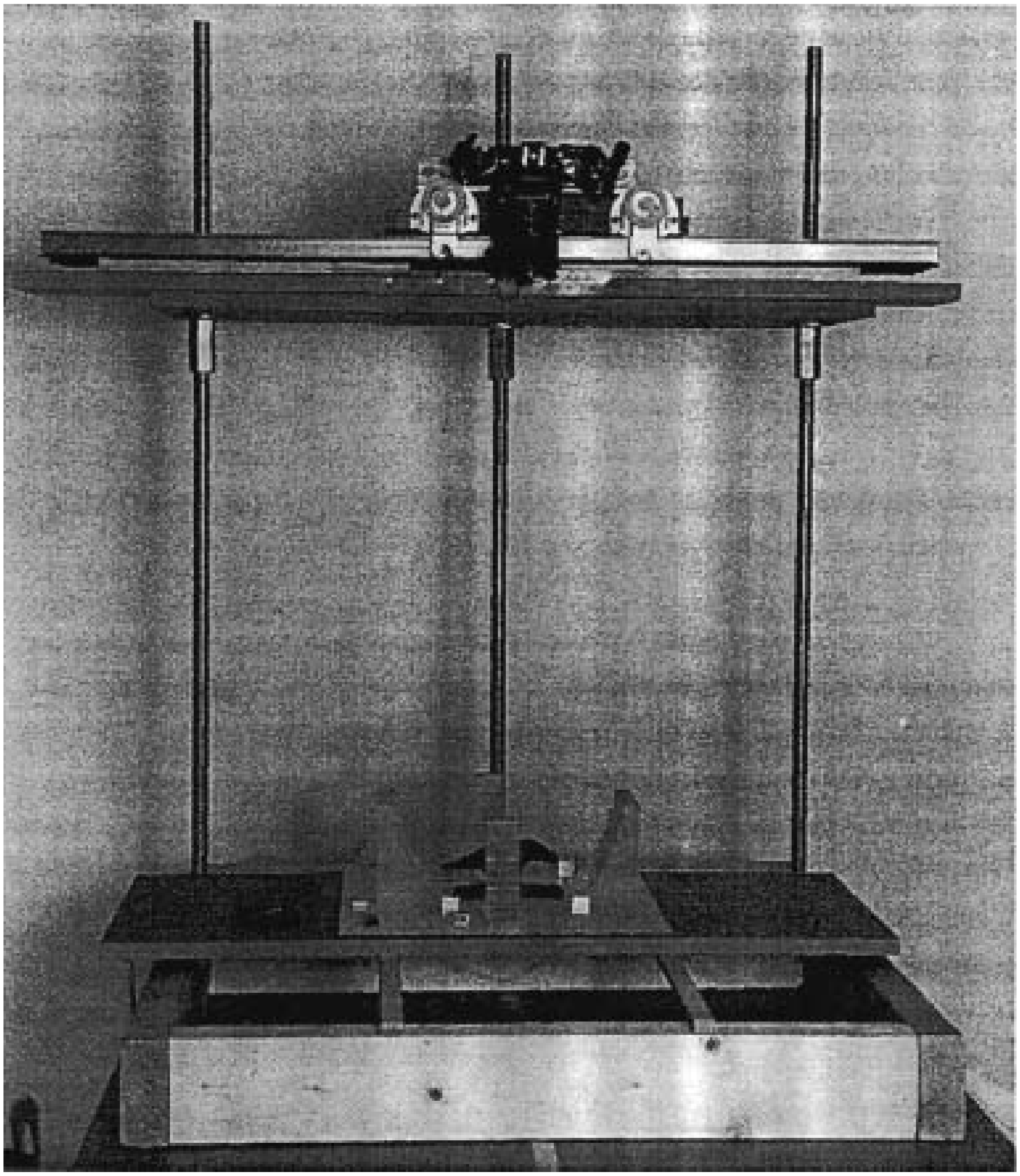


Figure 23. A system to control the object distance

both the camera and the control frame. Once the camera distance is set, the camera is placed so that the center of the control frame or artifact can be viewed in the center of the viewfinder, in this example referred to as the origin. Stereo photos are then shot by moving the camera by half the base distance to the left and then to the right of the origin. It is important to carefully view the setup in both the left and right positions. Important aspects to consider are:

a. Does shadow obscure either necessary control points or artifact features:
b. Does reflected light present a problem?
c. Will the corners of the image (film) have the necessary contrast (i.e. white background) in order to easily pinpoint them after scanning?
d. Are the artifact edges clearly defined and not blended with shadows?
e. Has all of the necessary information like camera distance, base distance, etc. been properly recorded?
f. Are all of the control points clearly labelled to avoid future confusion?
g. Are the proper labels visible in the images (i.e. provenance, accession numbers, etc.)?

5. Light source and lighting method

Recommended light sources are: 1) natural light which includes direct light from the sun, scattered sunlight from the sky and reflected sunlight from a reflection plate; and 2) artificial lights such as electronic flashes, floodlights and strobes. Lighting equipment may also include reflection plates, umbrellas, light meters, etc.

Undoubtedly, natural light is widely used in many kinds of photographs. However, for this project, the use of strobes is recommended. One can easily move from one kind of light system to another as soon as one is familiar with certain basic principles. For medium to small objects, the advantages of using strobe lights eliminate weather dependence unlike natural lighting, and the results are more predictable than an electronic flash lighting system. The process is moderate in price and generates less heat than a floodlight system which could be of importance when dealing with sensitive materials. Also, most artifact collections are housed indoors, and it is fairly easy to setup a small “studio” area near the collections.

For very large objects, the expense of an artificial lighting system will increase significantly, and one may need to take advantage of natural light sources. Proper choice of light sources and the correct illumination of objects are important factors in obtaining quality images.

Photo illumination systems should offer sufficient light to provide proper exposure to the films. A one-light system is suitable only for absolutely flat objects such as pictures. All three-dimensional objects cast a shadow which might result in possible loss of information. The size of the shadow cast, is proportional to the angle between the light and the camera. By reducing this angle one can minimize the shadow and possibly improve on the quantity of information obtained, however, by reducing the angle, one may perceive less texture and less three-dimensional visual effect.

For three light systems, using conventional photographic lighting setup, the main light is usually placed higher than the camera, at an angle of 30-60 degrees with respect to the line of sight of the camera. It should illuminate most parts of the objects, making most of the information recordable. To obtain better visual stereo results and retain texture of objects, careful adjustment of the main light is necessary. Generally speaking, the angle should be larger when the object is flatter or has a fine texture. The fill light, fills the shadow created by the main light. it is usually placed near the camera on the side opposite the main light, and somewhat lower than the main light (figures 24 and 25). The brightness of the fill light is usually one-half to one-eighth that of the main light. A brighter fill light offers more detailed information in the shadow created by the main light. In this project, our main purpose is to record as much information as we can. It is suggested that the ratio of fill to main light be about 1:2. To obtain the proper ratio between the main light and the fill light, one can adjust the distance or power of the fill light, based on proper light-meter readings. The back light separates the main objects from the background, in conventional photographic views. In this project, it is used to minimize the shadows in the background and to make the objects stand apart from the background so the edges of the artifact are distinctly visible (note various means of backlighting in figures 24,25 and 26). It is very important to achieve strong contrasts and clear outlines on all the four sides and corners of the film, which are the non-metric camera photogrammetry register points. This can be accomplished through the use of a white background (see figure 25).

Mirror reflection on a photograph can result in the obstruction of control points or even the artifact. It is therefore, a phenomenon one should be aware of when setting up a photography session. The relative position of the light source, object surface, and camera lens can cause the light to be polarized when it is reflected from a very smooth and flat surface. Polarized reflection can be reduced by carefully adjusting the photo setup or by using a polarizing filter. If using a lighting system that has the added feature of modeling lights, reflection can usually be detected through the view finder of the camera. One should place the camera in both the left and right position to check for reflection.

6. Exposure

Exposure, namely the shutter speed and f-stop setting, can be derived using manufacturer’s suggestions or with the help of a light meter. Given our particular photographic setup, we found that adding one full f-stop or slightly more exposure to the light meter reading yielded better image contrast and scanning resolution.

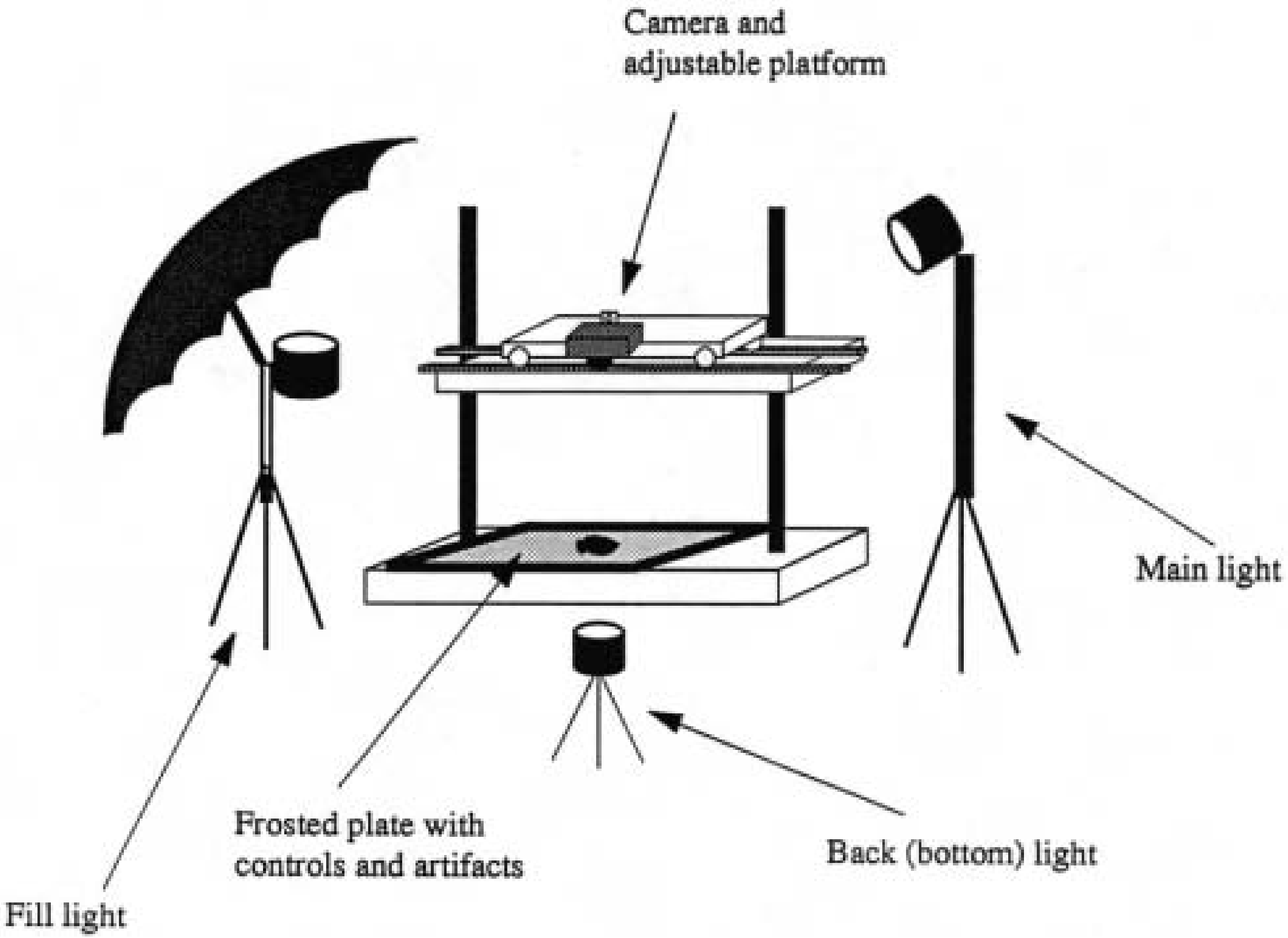


Figure 24. The lighting setup for vertical photography

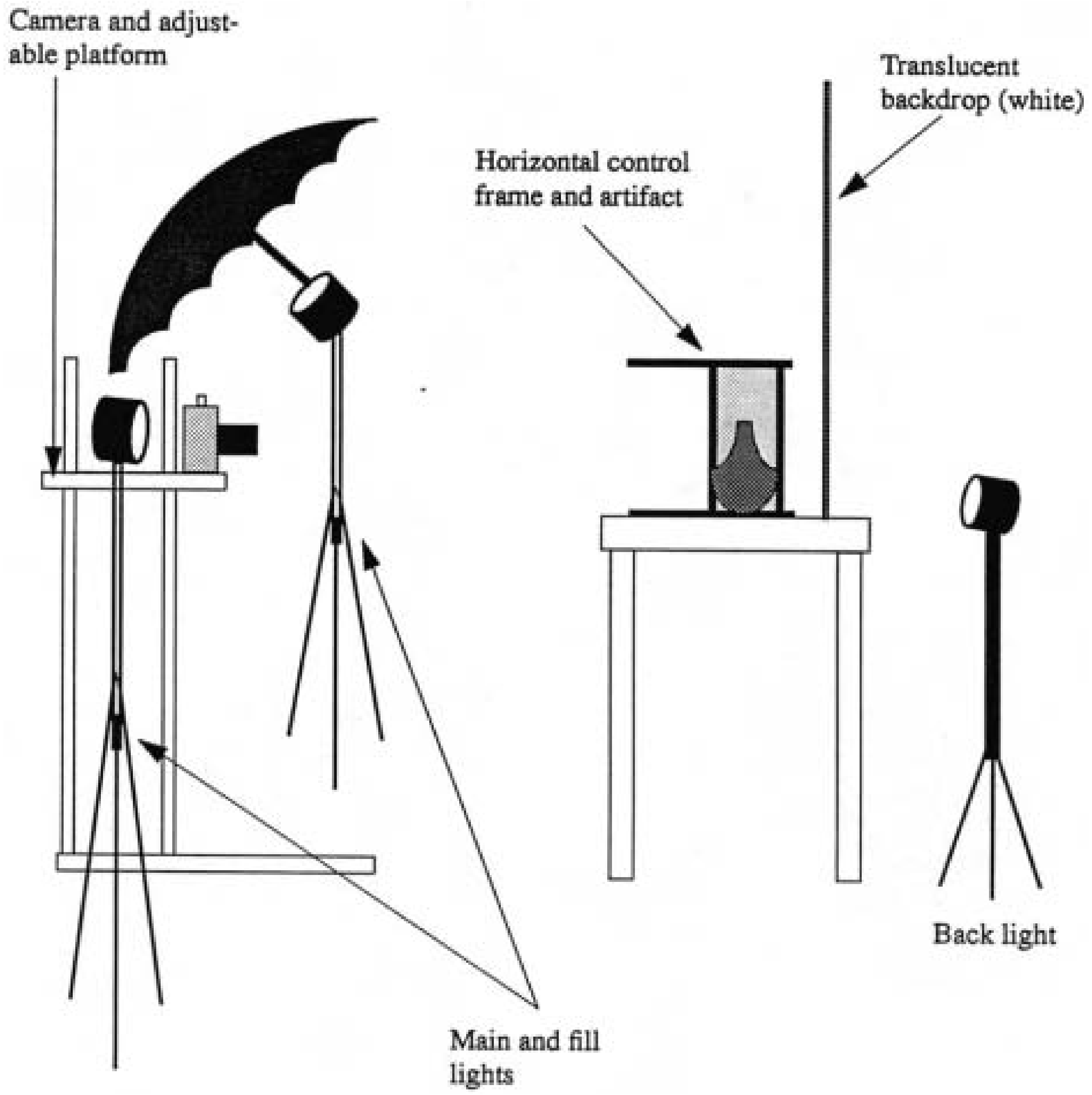


Figure 25. The lighting setup for horizontal photography

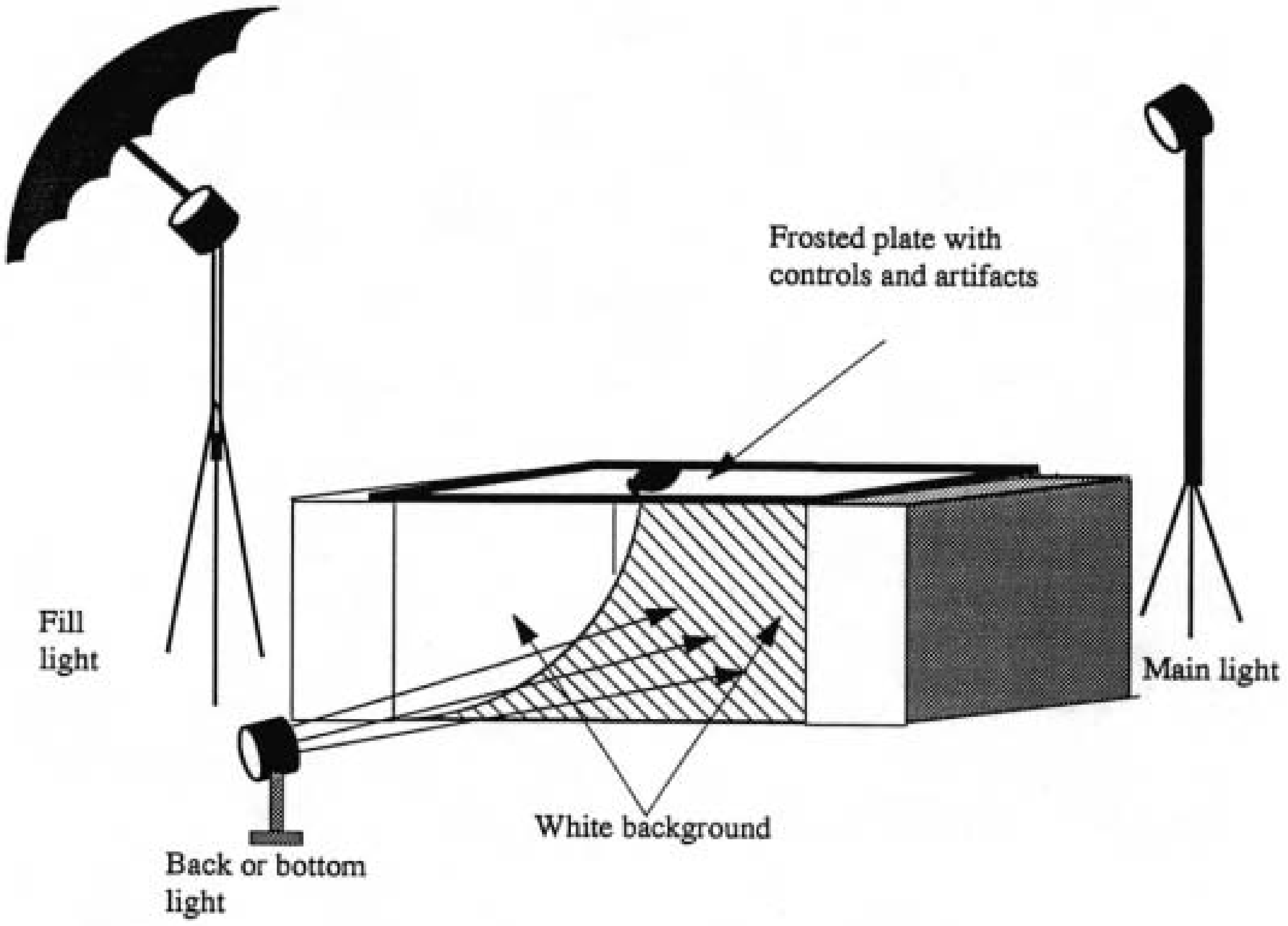


Figure 26. Backlighting for vertical photography

D. PROCESSING DATA WITH A SOFTCOPY PHOTOGRAMMETRY SYSTEM

The focus of this study has been the derivation of a low cost method to produce good quality stereo images. The photogrammetric processing of our images, however, was performed using a top of the line system which consists of the Intergraph ImageStation softcopy photogrammetric workstation and the Zeiss-Intergraph Photoscan high-resolution scanner. It is not expected that organizations interested in generating stereo images purchase such expensive equipment, but rather that they start documenting their collections for the day such systems become affordable. The market of computers is constantly revolutionized by faster processors, and better - data storage components, while at the same time prices are becoming more and more affordable. It is reasonable to expect that within a few years, personal computer systems offering the same kind of capabilities as the Image Station will be available. As a matter of fact, Intergraph has already started the process of porting their photogrammetric software to the NT-PC environment.

The ImageStation located at the Center for Advanced Spatial Technologies has a 27-inch display with a 120 times-per-second refresh rate, twice that of a standard computer screen. It is this feature which makes possible the stereo imagery. The left and right images are displayed alternatively every half-second. Crystal liquid shutter glasses are in synchronization with the display and allow each eye to see only one image. A special board, the Vitec VI5O, takes care of image display, allowing the user to fly in real-time over the stereo images. Another board compresses and uncompresses the data files every time they are accessed. This component is essential since compressed data can be stored using about a seventh of the disk space necessary for uncompressed file without slowing down the operator’s work. The ImageStation is connected to the Photos can scanner (see figures 27 and 28), a joint product by Intergraph and Zeiss, which transforms analog film transparencies to digital form. Photoscan can scan at resolutions of 60, 30, 15 and 7.5 micrometers. The lower the number, the finer the resolution and the larger the size of the resulting files.

A number of 35 mm slides were scanned at 7.5 micrometer resolution in three passes, one for each color band. The size of each resulting band is 22 Mb before compression and 3.5 Mb after compression. A pair of photos uncompressed would require about 132 Mb and a compressed pair about 20 Mb. For purposes of comparison photographs were also processed using a standard office seamier (see figure 29). The scanner had a resolution of 400 dots per inch (dpi) which is equivalent to 60 micrometers. This type of scanner was designed to process opaque paper, and the slides had to be printed and enlarged to compensate for the lower scanning resolution. Two slides were enlarged to 8x10 inches. Since standard 35 mm cameras do not have fiducial marks, the corners of the film window were used in order to perform the 10. Because regular enlargements do not include the actual corners of the film window, the operator must be reminded not to crop the

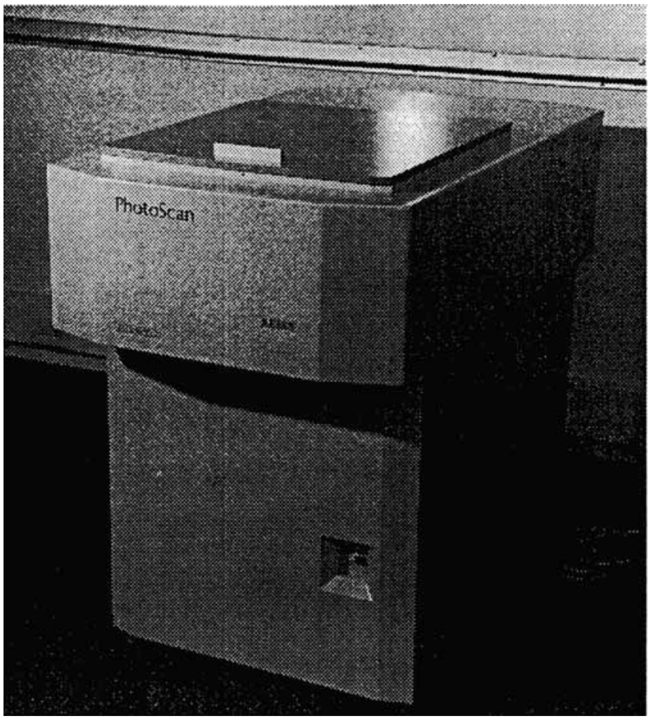


Figure 27. The Zeiss-Intergraph Photoscan scanner

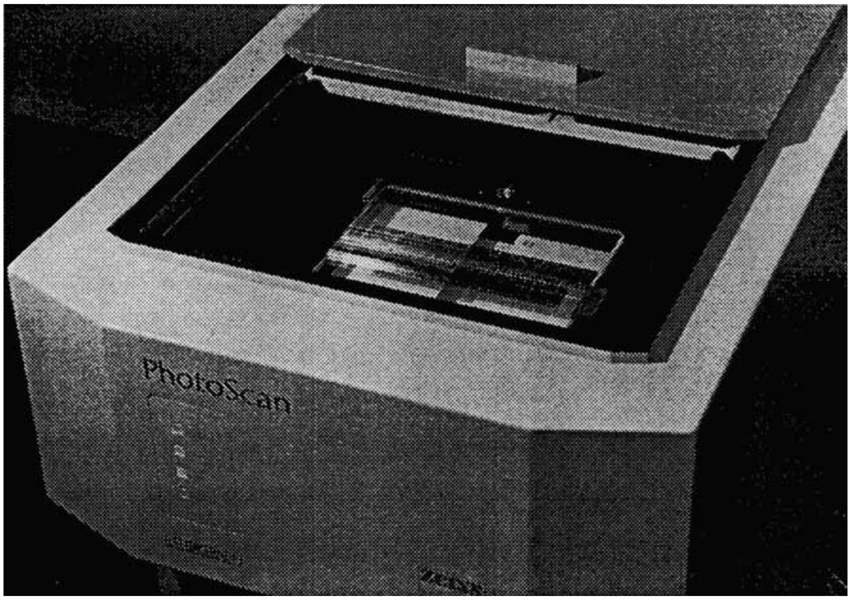
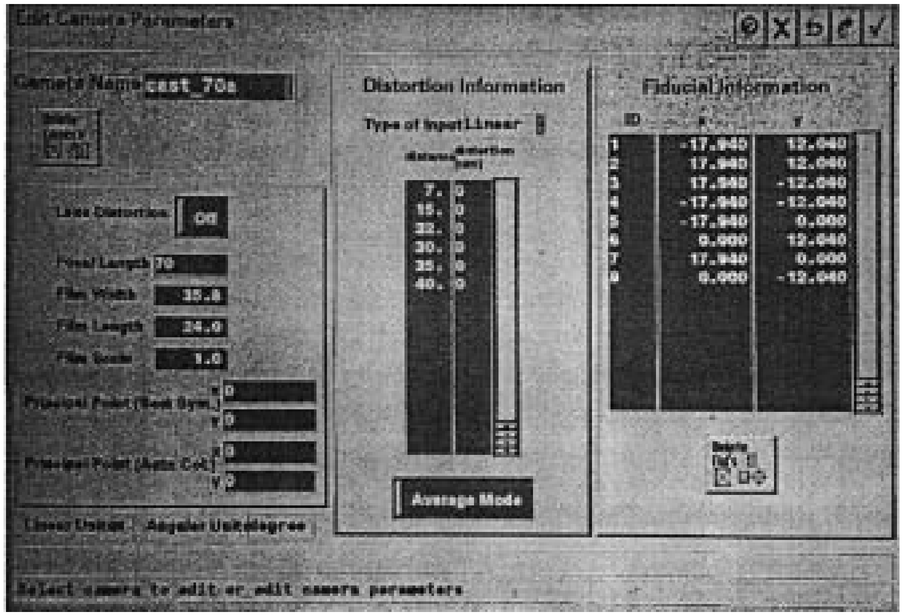


Figure 28. Inside the Zeiss-Intergraph scanner

Figure 29. A typical office flat-bed scanner



Camera Name: cast_70s

Lens Distortion: On

Focal Length: 70

Film Width: 35.8

Film Length: 24.0

Film Scale: 1.0

Principal Point (Best Sym.) x: 0 y: 0

Principal Point (Auto Col.) x: 0 y: 0

Linear Unit:mm Angular Unit:degree

Distortion Information

Type of Input: Linear

distance	distortion (um)
7.	0
15.	0
22.	0
30.	0
35.	0
40.	0

Fiducial Information

ID	x	y
1	-17.940	12.040
2	17.940	12.040
3	17.940	-12.040
4	-17.940	-12.040
5	-17.940	0.000
6	0.000	12.040
7	17.940	0.000
8	0.000	-12.040

Select camera to edit or edit camera parameters

Figure 30. Defining camera parameters

image and most importantly, to make sure the frame around the image is visible. The enlargements were scanned at 400dpi and processed on the ImageStation in the same manner as the 35 mm slides. The obtained digital three-dimensional measurements proved to be of similar accuracy. Another scanning format which was considered was the Kodak “Photo CD.” This product can be obtained from many photoprocessors and is a CD product that includes files that represent the photograph. While the process would appear to hold great promise, the standard process cannot be altered and crops the edges of the frame. Since the edge of the frame was not present on the CD image, the frame could not be subjected to interior orientation (IO), and the product could not be used. In the event that a camera with fiducials or a reseau plate was used, it would be possible to perform the IO on an image that was slightly cropped, and this method should be considered.

Once in digital form, the stereo pairs are ready to be processed. However, prior to performing the orientation tasks, the system needs some information regarding the camera interior and the shooting setup.

First the camera must be defined. Through a series of dialogue boxes (see figure 30), the system will request information such as the lens focal length, the film size and the coordinates of the fiducials, in this case, the corners and potentially the middle of the edges. The film size is, in reality, that of the film area actually exposed to the light. Using the scanning software, we were able to obtain an estimate of its size: 35.88 mm by 24.08 mm, for our Minolta camera. The coordinates for the corners can then be inferred from this information and provided to the software with respect to the center of the film (see figure 31). These will be referred to as measured coordinates.

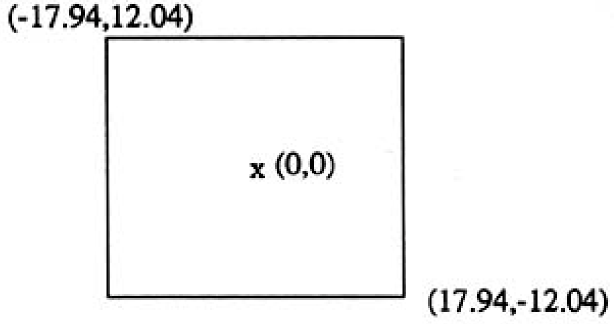


Figure 3 1. Coordinates for corners or 35 mm film

Looking at figure 30, one can see that lens distortion information can also be entered at this stage of the process. Such data are normally provided as part of the metric camera calibration process. Since the cameras used in this project were not calibrated, this information could not be entered. Next, the information regarding the camera position versus the object control field must be provided. This includes the object distance (or flying height), base distance (or air base) and average depth (or elevation) of the control field. The overlap is automatically computed by the software. The orientations can then be performed.

1. Interior orientation (IO)

Normally the process of interior orientation (IO) involves association of the fiducials with their measurements. In this study the process consists primarily of associating the corner of the film frame displayed on the screen with its measured coordinates. This operation will have the effect of rotating the image to recreate the orientation it had in the camera at the time of exposure, as well as to compensate for phenomena such as film expansion, shrinkage or lack of flatness. Figure 32 shows a typical setup to perform the IO. A window is displayed which contains the full film frame and two windows displaying a zoomed-in area of the film corner under consideration. The screen also has a form allowing adjustment of the image contrast (bottom-right), and there is a list of the fiducials and the results from the transformation. The user chooses a fiducial from the list and then dynamically selects the location of the corresponding corner on the screen. Once data on all fiducials have been entered, the software performs a mathematical transformation to compute the best match between the corners identified by the user and the measured information. The solution can be computed using conformal, affine or projective transformations. The conformal model is recommended when dealing with non-metric cameras (Fryer, 1992), and our experimentation also showed an improvement over using the affine transformation. The 10 results as presented by the ImageStation software are shown in figure 33. For each fiducial the system displays the measured coordinates from the camera file (in millimeters), those of the points selected on the image (in pixels) and the residuals (in micrometers). The latter is the result of the difference between the measured and observed sets of coordinates after a best fit transformation has been applied. Sigma represents the standard deviation or root mean square error (RMSE):

$$RMSE = \sqrt{\frac{\sum r^2}{d}}$$

where r stands for the residuals and d for the number of degrees of freedom.

A low sigma is indicative of a good solution. For the applications in this study, a value of sigma lower than 10 is acceptable but a value of 5 or lower yields more satisfactory results. Although a low sigma is desirable, attempting to adjust the position of the fiducial marks until the RMSE becomes very small is a waste of time, due to the accuracy of the measured coordinates and the fact that the camera interior is not controlled.

The conformal transformation requires more than two fiducials to generate

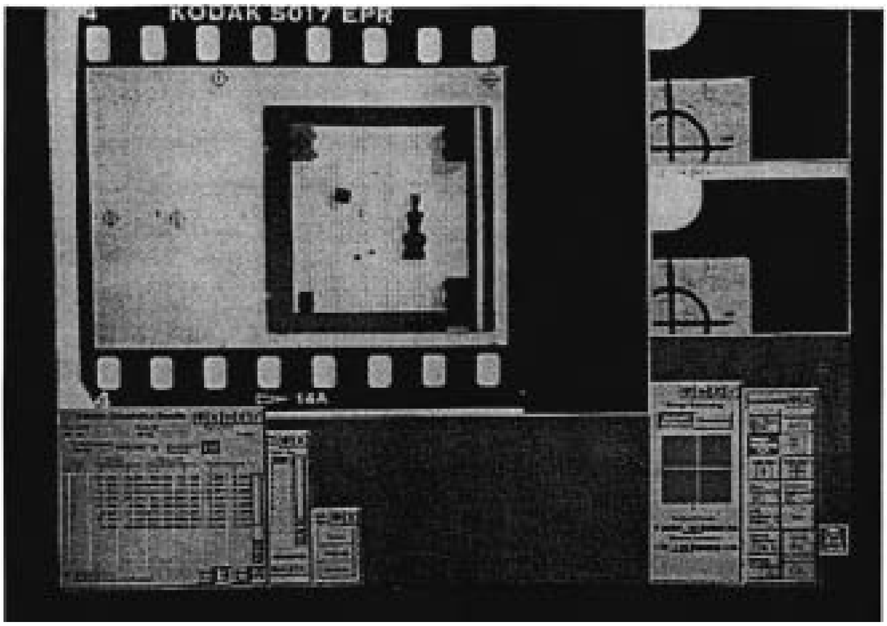
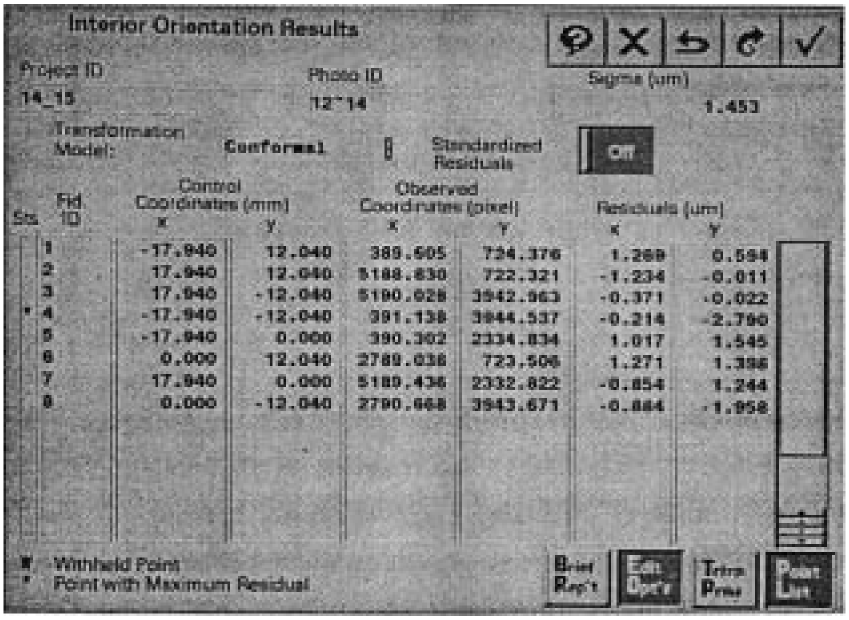


Figure 32. Performing the interior orientation



Interior Orientation Results

Project ID 14_15

Photo ID 12^14

Sigma (um) 1.453

Transformation Model: Conformal

Standardized Residuals: Off

Sts.	Fid. ID	Control Coordinates (mm) x	Control Coordinates (mm) y	Observed Coordinates (pixel) x	Observed Coordinates (pixel) y	Residuals (um) x	Residuals (um) y
	1	-17.940	12.040	389.605	724.376	1.269	0.594
	2	17.940	12.040	5188.830	722.321	-1.234	-0.011
	3	17.940	-12.040	5190.028	3942.963	-0.371	-0.022
*	4	-17.940	-12.040	391.138	3944.537	-0.214	-2.790
	5	-17.940	0.000	390.302	2334.834	1.017	1.545
	6	0.000	12.040	2789.038	723.506	1.271	1.398
	7	17.940	0.000	5189.436	2332.822	-0.854	1.244
	8	0.000	-12.040	2790.668	3943.671	-0.884	-1.958

■ Withheld Point
* Point with Maximum Residual

Figure 33. Interior orientation results

redundancy, and therefore one should have at least four to obtain a good fit. Most analytical plotters have a software allowing interpolation of the corner coordinates from points digitized along the edges. This capability offers a better alternative to using film corners which are often fuzzy or irregular. Unfortunately, since the ImageStation has been primarily developed to handle data generated with metric cameras, it does not have a program allowing the performance of such an operation. Our remedy was to use the middle of each edge as an additional fiducial. Although not very accurate and very subjective (there are no marks on the photographs to locate them), this method provided more redundancy and took into account edges as well as corners.

The latest version of the ImageStation software has been enhanced to handle "reseau" - data (see discussion on metric and non-metric cameras). It will perform a second transformation generating a best fit solution for the reseau marks only. These points are distributed over the photographed area. By applying a transformation based on them, variations due to lens distortion or film unflatness can be partially compensated for. Once the interior orientation is completed, the software allows the user to go on to the next step, the relative orientation.

2. Relative orientation (RO)

The relative orientation process consists primarily in rotating the two images to make them parallel to each other, and therefore, to guarantee accurate stereo-viewing. This task is especially necessary for aerial photography, where the position of the plane tends to vary from picture to picture. The software presents the user with the two images (see figure 34) for which common features must be selected. When the user has identified enough common points, a best fit solution is computed resulting in a set of residuals and a RMSE. In this study, the values for sigma varied between 0.4 to 8 micrometers.

3. Absolute orientation (AO)

Prior to proceeding, the user must first provide the software with a list of labeled points and their three-dimensional coordinates. These points, called controls, should consist of marked, measured and tagged features which have been selected on the object or control frame prior to the photo shoot. The absolute orientation (AO) process assigns a scale to the stereo model by associating the controls' coordinates with the corresponding features on the left and right images. The software will ask the user to identify on each picture, the corresponding control point. In figure 34, a target located on the upper left corner of the frame, has been selected. The area surrounding it is automatically shown in the two zoom windows to allow a better placement of the control point. As was true for the 10 and RO steps, a best fit transformation is performed. The absolute orientation form shown on figure 35 shows a wealth of information regarding the corrections which had to be applied to each image to fit the controls. The user is primarily

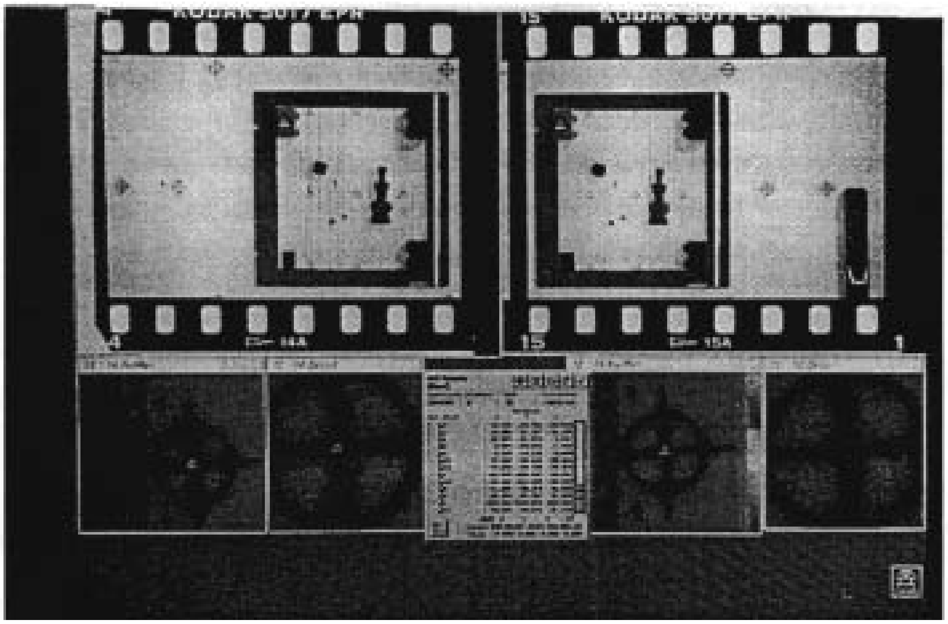


Figure 34. Performing the relative and absolute orientation

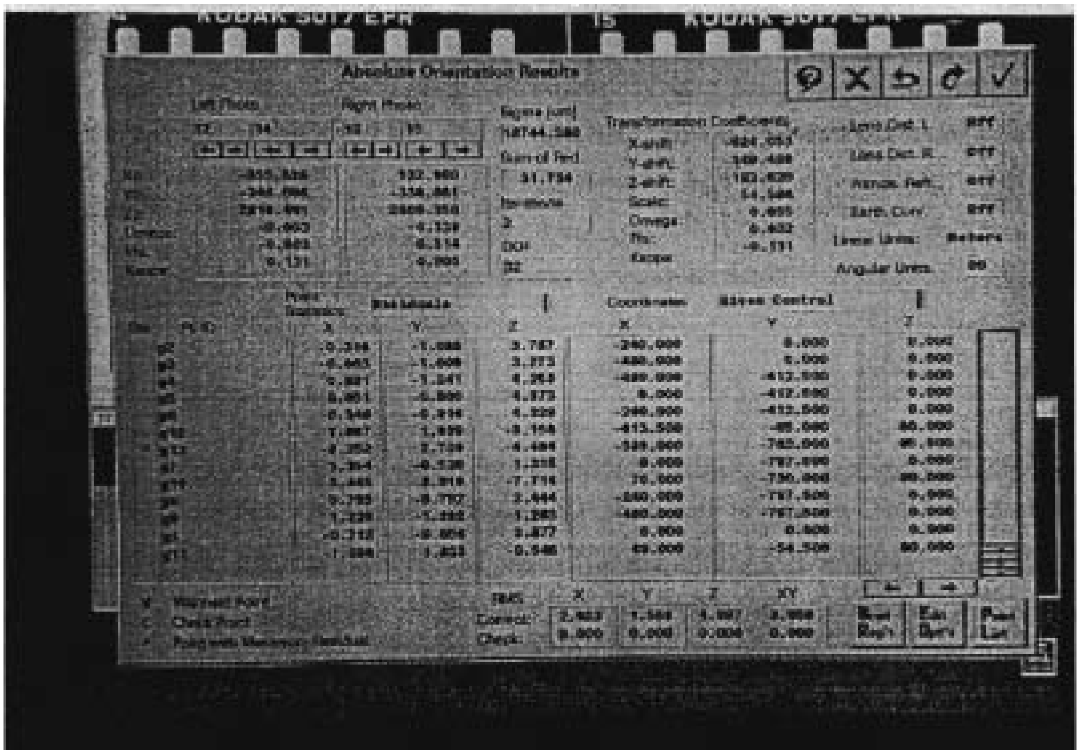


Figure 35. Absolute orientation results

interested in the residuals and the sigma or RMSE. The latter is provided for all axes together as well as separately. In the solution shown in figure 35 the RMSE value for the z axis (depth) is slightly worse than that for x and y. The best solution is computed using least square adjustments. Using this mathematical model, it is important to make sure that the value for sum of redundancies and the number of degrees of freedom (DOF) are equal or at least very close. If they are not, the solution obtained is invalid. In figure 35 for example, the sum of redundancies is 3 1.734 and DOF is 32, therefore the result is valid.

The value displayed in figure 35 for the overall sigma would appear to be extremely high, namely 18,744. In fact, the values we have obtained throughout our study range from near zero to almost 100,000. These large values are artifices of the measurement units that are required in systems designed for aerial or architectural photogrammetry. These very large values would not be generated from photogrammetric system which would allow the entry of very small working units (e.g. centimeters or millimeters) which would be appropriate for the size of the objects used in this study. The ImageStation was primarily designed for aerial and architectural applications, as are most softbench photogrammetric systems. For this reason, the software expects the working unit to be meter or feet. In our case, providing measurements in meters caused all residuals and RMSE returned during the absolute orientation computation to be zeros. Our solution to this problem has been to multiply by 100 all values for the control points, object distance (or flying height), base distance (or airbase) and average depth, effectively causing the system to use centimeters as the working unit. This, however, had the unfortunate side-effect of disturbing the relationship between the image coordinates expressed in micrometers and those of the actual object. Indeed instead of dealing with a maximum depth of 0.4 meter, the ImageStation is being told that it is 40 meters. Therefore the scale or relationship between the image and the real-life object is exaggerated, and leads to a displayed sigma much larger than expected. Effectively this number has been increased by the square of 100 and when this is factored into the assessment the apparently large sigmas do not affect the measured results. This adjustment to normal aerial operation allowed the handling of small objects and yielded good results. To process images of even smaller areas (areas of ten by ten centimeters), the same parameters had to be multiplied by ten thousand instead of one hundred. A depth of 0.005 meter was entered as 50 instead, i.e. the working unit effectively became a tenth of a millimeter. Except for the fact that these numbers are extremely un-intuitive, a very good AO solution was achieved.

4. Stereo resampling and image analysis

Once best fit solutions have been reached for the interior, relative and absolute orientations, a new and corrected stereo pair is created during the process of stereo resampling. The resulting stereo model can then be displayed in stereo on the computer screen. The computing power of the Intergraph ImageStation allows the user to move about the stereo pair as if “flying” over the actual scene or object. It is possible to zoom in or out so as to view features at the level of detail desired. In figure 36, for example, the screen has been divided into four windows or views. The one on the upper right represents a set of beads, and the three others are zoomed in views of each individual bead. The user can define as many views as necessary, either displayed side by side or overlapped. Each can be viewed in stereo mode or not, however, only one can be roamed dynamically. An efficient way to set up views is to have one as large as the screen which can be roamed and several other smaller stereo ones which focus on various objects or features of interest. A large pointing device, called the track-ball, enables the user to control movements along the x, -y and z axes, while dynamically displaying the real-life coordinates of the cursor’s current position. Therefore, one always knows the three-dimensional coordinates of the location at which the cursor is positioned. It takes a little time to learn how to “land” the cursor correctly on a surface, but we found that different operators with the same level of skills obtained very consistent results.

The CAD software Microstation and Microstation Feature Collection are integrated into the ImageStation Data Collection environment and allow the digitization in three dimension of features such as roads, an artifact’s profile, a pot’s rim or outline (see figure 37). Microstation offers a palette of predefined three-dimensional shapes, e.g. cylinders, rectangular blocks, spheres, circles, which can be used to quickly digitize the shapes of artifacts. Figure 38 shows a sphere and a cylinder displayed from four different angles. Independent rotation can be applied to each one of these views. The resulting digitization process can create a standard CAD format data file which can be exported to a large suite of other software for display or further analysis.

It is also possible to generate an elevation surface which can be converted to a DEM or to contour lines. To do so the user first defines the area to be modelled and a grid is then displayed. The user must place or “land” the cursor on selected points while viewing the pair in stereo. Once all points have been entered, the software interpolates the information and generates a surface. The results of application of this process to the surface of a large animal bone are shown in figure 39. To create this product, a one-centimeter grid was first displayed and the cursor was manually landed on each intersection creating a very coarse matrix of elevation values. A half-centimeter grid was then displayed to generate a refined version of the surface. Once a coarse surface is available to the software, it can automatically place the cursor at an interpolated depth assisting the user in generating more accurate information. This process is very tedious and time-consuming to perform manually. Third party software called MATCH-T is available for the Photostation which is designed to automatically generate elevation values for terrain and could potentially be used to create elevation surfaces of artifacts. We were unable to obtain this software during the project but hope to obtain it in the future and evaluate the results of automatic elevation matrix extraction. Based on published information, it appears likely that the method will be

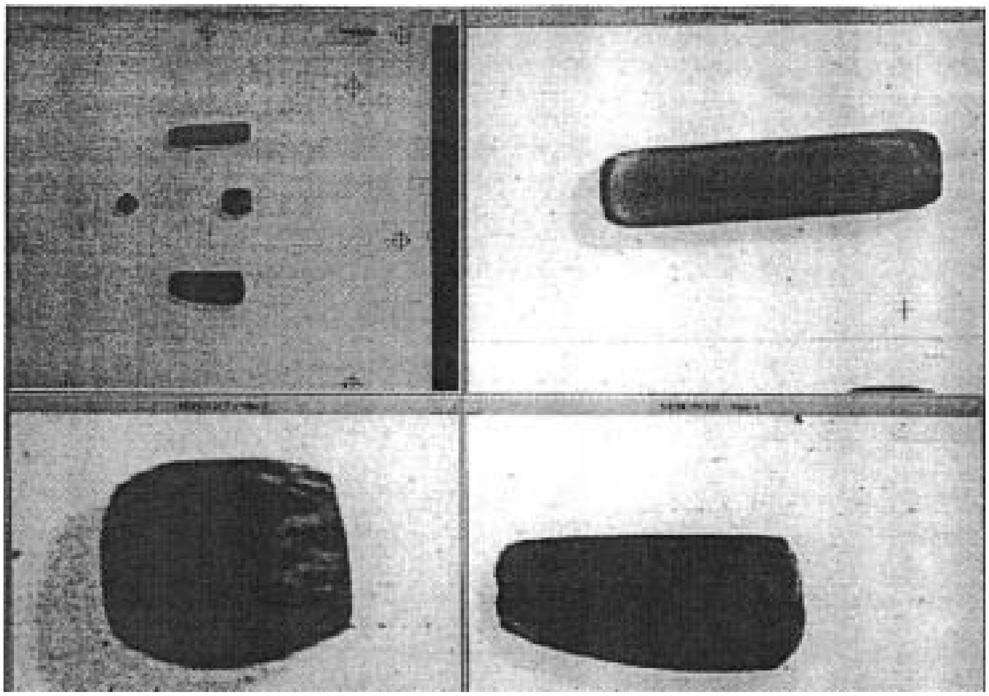


Figure 36. Zooming in on an artifact’s details

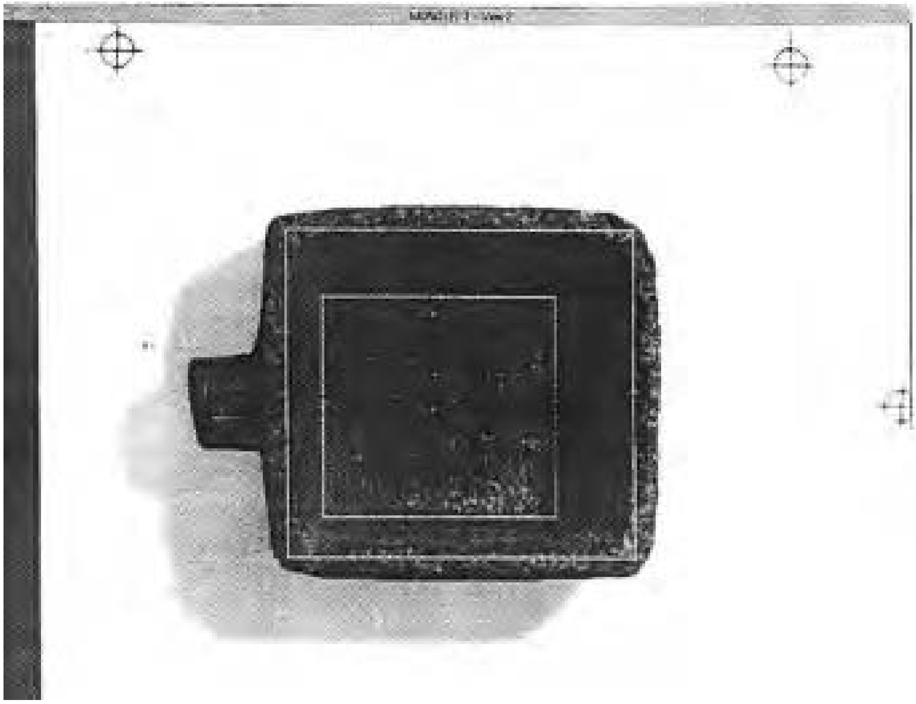


Figure 37. Digitizing artifacts

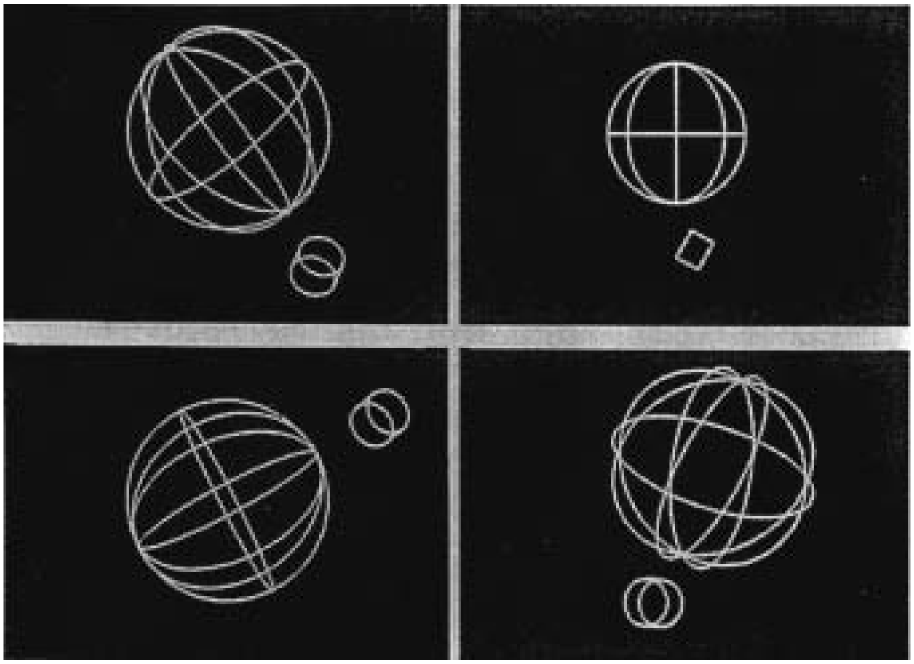


Figure 38. Examples of Microstation’s ability to handle three-dimensional wireframes

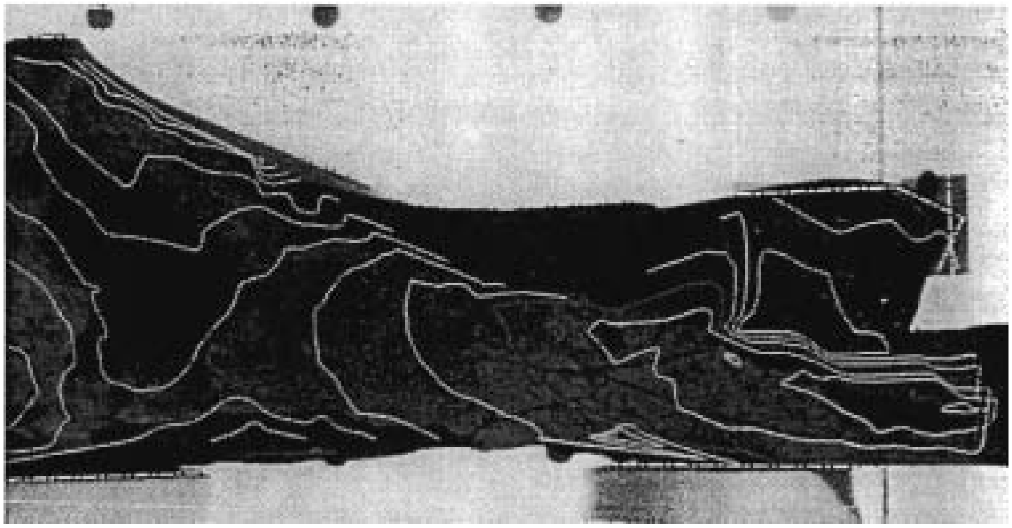


Figure 39. The generation of elevation surfaces represented as contour lines

effective in situations where there are complex details or texture on surfaces but may not be effective on objects with uniform surfaces with low contrast or texture.

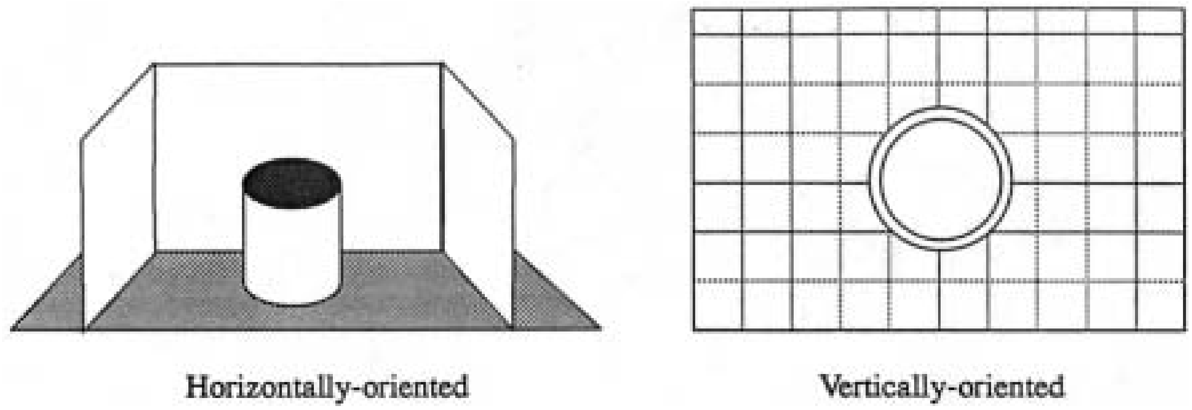
In conclusion, the use of the Intergraph ImageStation has allowed the photogrammetric preparation of the 35 mm stereo photographs so that three-dimensional measurements could be extracted. Assessment of the accuracy obtained compared to that of manual measurements is discussed in the following section.

RESULTS

The following discussion on results is based on imagery produced by two cameras, a Minolta X-700 and a Nikon F-3. The Nikon was equipped with a 55mm Nikkor lens and the Minolta had a 28-70mm zoom lens. These two systems were used in two different photographic approaches. In one the camera was positioned horizontal to the object, as would be the case in photographing larger items (see figure 25), and in the other the camera was mounted vertically, above the object (see figure 26). This latter configuration would be common in photography of smaller items. For the most part the discussion will deal with products from the vertical camera configuration but some space will also be devoted to results produced by the horizontal one. In addition to cameras and configuration, the following also considers the impact of different control frame structures on the final results.

In the following, we will compare a suite of measurements taken on objects using manual and digital methods. For each object the same individual identified the characteristics or locations on the object for both sets of measurements. Laboratory measurements were obtained by an individual with extensive experience and included traditional measurements such as an object's width. In other instances, a location was selected to be reflective of specialized measurements that might be taken, such as a prominence on the flaked surface of a chipped stone artifact. Normal venier calipers were used whereever possible. It should be emphasized that manual measurements were not known when the softcopy results were obtained. The same experienced archeologist, trained in the use of the Intergraph system, first obtained softcopy measurements and then took manual measurements of the same artifact features. Thus, the softcopy practitioner needed to identify the appropriate measurement location on the image of the object (widest point of the projectile point, for example) just as the archaeologists would in the laboratory.

The following tables will show the manual (vernier calipers) and digital (3-D softcopy) measurements for a variety of artifacts, and the differences for these measurements obtained by subtracting the manually derived measure from the softcopy derived one. All of the following tables show the depth (z value) measurements at the top and the horizontal (x and y) measurements at the bottom. The third dimension corresponds to the z value and for the purpose of this discussion, is referred to as depth. It should be noted that for horizontally-oriented photography it indeed corresponds to depth or width, however, for vertically-oriented photography, depth actually refers to the "height" or "elevation" of the artifact photographed (see figure 40). The units used throughout this section are millimeters. The measurements from both manual and softcopy procedures have been expressed to hundreths of millimeters. The readout from the softcopy system was provided in these units as was the readout from the calipers. It is unlikely that such precision is truly possible for many manual or softcopy observations given the limits of the control frame and the cameras used, but the values as recorded by the individual performing the work have been preserved here for reference purposes.



Horizontally-oriented Vertically-oriented

Figure 40. Vertically- and horizontally-oriented photography

In order to assess the impact of shape, size, and materials on the results a range of artifacts was utilized: a modern ceramic flower pot, a hand-blown glass pitcher, a civil war cannister shot, prehistoric chipped stone adzes, a carved ivory pendant, a small stone bowl, and a very small glass bead.

A. SMALL OBJECTS AND SMALL VERTICAL CONTROL FRAME

A series of images of small objects (a pendant and a bead) were taken with a Nikon camera with a Nikkor 55mm lens, and a camera distance of 40 cm. The results from this system using the small vertical type of control frame (figure 14) appear quite good. All softcopy measurements vary from the manual measurements by no more than one-half of a millimeter (see table 5).

Deviations between the two measurement approaches vary from a low of 0.04 mm to a high of 0.39 mm. The deviations from manual to softcopy for the small glass bead is the highest in both vertical and horizontal measurement. Though it is relatively hard to accurately manually measure an object that is this small, the deviations are still within only a few tenths of a millimeter. These measurements reflect the same individual attempting to obtain the same measurement from the same reference point on the objects. It seems likely that the difference here would be smaller than that expected from two different individuals measuring the same item manually.

Table 5. Small vertical control frame

Type of Artifact Measured	Manual Measured Value (mm)	Digital Measured Value (mm)	Difference in Values (mm)
	Depth (Z)	**Depth (Z)**	**Depth (Z)**
Pendant	**5.45**	**5.49**	**0.04**
Bead	**1.63**	**1.93**	**0.30**
	Horizontal (x or y)	**Horizontal (x or y)**	**Horizontal (x or y)**
Pendant	**10.80**	**10.84**	**0.04**
Pendant	**10.70**	**10.53**	**-0.17**
Pendant	**29.65**	**29.49**	**-0.16**
Bead	**2.45**	**2.26**	**-0.19**
Bead	**2.60**	**2.21**	**-0.39**

B. SMALL AND MEDIUM SIZE OBJECTS, LARGER VERTICAL CONTROL FRAME

The next image sets were prepared utilizing a different control frame (figure 16) and two different cameras (the Minolta and the Nikon). The same control frame, objects and camera distance were used for all the objects but the focal lengths and, therefore, base distances (or camera movement) were different.

In looking at tables 6 and 7, one can see that the z axis (depth) measurements have the greatest deviation when the object measured has greater depth. The z-axis difference is approximately 1 cm for the Nikon camera and 1.5 cm for the Minolta. The difference between these cameras can likely be attributed to the usage of a zoom vs. a lens with a fixed-focal length as well as to the unique optic distortion of each camera and lens. No matter what the specifics of the camera system, however, there is a general tendency for the absolute amount of deviation from manual to softcopy measurement to increase as the height of the measurement increases above the base reference plane. In a later section in this report we will return to this factor and discuss its impact and ways in which it may be accommodated in a lowcost recordation system. It is well documented in the photogrammetric literature that radial distortion and film unflatness can introduce very significant errors and it is precisely these errors that are addressed in the expensive metric cameras and the calibration reports prepared for them. Fryer et al. (1990) demonstrated that results can be significantly improved by compensating for radial distortion, as we will discuss later.

Table 6. Large vertical control frame (Minolta)

Type of Artifact Measured	Manual Measured Value (mm)	Digital Measured Value (mm)	Difference in Values (mm)
	Depth (z)	**Depth (z)**	**Depth (z)**
Ceramic Pot 1	**95.60**	**109.49**	**13.89**
Ceramic Pot 2	**96.20**	**112.28**	**16.08**
Adz 1	**18.50**	**18.92**	**0.42**
Adz 2	**12.75**	**11.92**	**-0.83**
Adz 3	**20.10**	**19.02**	**-1.08**
Adz 4	**10.30**	**6.48**	**-3.82**
	Planar (x and y)	**Planar (x and y)**	**Planar (x and y)**
Ceramic Pot 1	**126.45**	**123.01**	**-3.44**
Ceramic Pot 2	**130.50**	**125.18**	**-5.32**
Adz 1	**58.15**	**57.93**	**-0.22**
Adz 2	**38.15**	**37.75**	**-0.40**
Adz 3	**39.50**	**39.95**	**0.45**
Adz 4	**80.95**	**80.79**	**-0.16**
Adz 5	**42.20**	**42.32**	**0.12**

Table 7. Large vertical control frame (Nikon)

Type of Artifact Measured	Manual Measured Value (mm)	Digital Measured Value (mm)	Difference in Values (mm)
	Depth (Z)	**Depth (Z)**	**Depth (Z)**
Ceramic Pot 1	**95.60**	**86.73**	**-8.87**
Ceramic Pot2	**96.20**	**86.65**	**-9.55**
Adz 1	**18.50**	**18.03**	**-0.47**
Adz 2	**12.75**	**13.28**	**0.53**
Adz 3	**20.10**	**19.06**	**-1.04**
Adz 4	**10.30**	**11.08**	**0.78**
	Planar (x and y)	**Planar (x and y)**	**Planar (x and y)**
Ceramic Pot 1	**126.45**	**126.78**	**0.33**
Ceramic Pot 2	**130.50**	**130.35**	**-0.15**
Adz 1	**58.15**	**58.03**	**-0.12**
Adz 2	**38.15**	**37.90**	**-0.25**
Adz 3	**39.50**	**38.90**	**-0.60**
Adz 4	**80.95**	**80.63**	**-0.32**
Adz 5	**42.20**	**42.01**	**-0.19**

For the smaller artifacts (e.g. adzes), which range in depth from approximately 1 to 2 cm, the difference between the digital and manual measurements are quite low. Overall, the results are slightly better for the Nikon camera, and this proves to be the case for almost all measurements in this report. With the exception of adz measurement 4 in the Minolta stereo pair, the results for depth (z value) measurements taken from the softcopy 3-D images for both cameras, are basically below one millimeter of error and the planar measurements deviations were under one-half of a millimeter, when compared to the manual measurements. These results seem quite acceptable for most demands and likely display no more variation than would be seen by manually measuring the artifacts several times in a lab situation. It should be pointed out that these specific artifacts were not specially prepared as was suggested earlier in this report, i.e. application of crosshairs, etc. The large error of adze 4 can likely be attributed to human error in landing the cursor on the “surface” of the artifact while measuring on the softcopy 3-D image. As we have discussed, in the absence of distinguishing texture or contrast, correctly placing the cursor on the vertical point of an object can be quite difficult and such was the case for adze measurement 4.

In general, the planar, or x and y, direction measurements resulted in quite acceptable error or difference between manual and digital measurements. For the most part, these differences result in less than one-half of a millimeter and for most applications one should be very pleased with this measurement accuracy from the softcopy 3-D images. The exception to this is found when measurements greater than 100 mm were taken from the Minolta stereo pair. In this situation it appears likely that the measurements either were located near the image edge or in an area of particular distortion. We will discuss this in more detail below. With this exception, it is quite clear that little information is lost when utilizing photogrammetric techniques as a method of recording small artifacts.

C. LARGER OBJECTS AND HORIZONTAL CONTROL FRAME

Following the method utilized for analyzing the error for the vertical setups, we will now look at the horizontal type of control frame (figure 11) and the error derived from this testing. The figures in the following table (table 8) were taken from two different stereo pairs, though they utilize the same horizontal frame and camera, the Minolta. As was the case for the vertical control frame images, deviations appear to be increasing with the depth of the object but there is also increased error for the horizontal measurements where the horizontal values are initially large. Deviations range from 2.68 to 9.22 mm in the vertical axes and from 0.37 to 3.39 mm in the horizontal. While the absolute size of the deviations using this camera and control frame combination is not as low as those produced in the above examples, it must be recognized that the objects considered are larger and therefore larger deviations can be expected. Indeed, larger objects have a greater depth and/or extend the measurements towards the image edge more than smaller objects. In fact, the depth, or z value, measurement deviations seen at the bottom of table 4 are slightly better than those from the vertical frame for a similar depth.

Table 8. Minolta camera and horizontal control frame

Type of Artifact Measured	Manually Measured Value (mm)	Digitally Measured Value (mm)	Difference in Values (mm)
	Depth (z)	**Depth (z)**	**Depth (z)**
Ceramic Pot 1	**128.90**	**138.12**	**9.22**
Miniball 1	**41.25**	**38.57**	**-2.68**
Pitcher 1	**100.15**	**103.49**	**3.34**
	Horizontal (x and y)	**Horizontal (x and y)**	**Horizontal (x and y)**
Ceramic Pot 1	**126.10**	**122.71**	**-03.39**
Miniball 1	**41.35**	**41.80**	**0.45**
Pitcher 1	**95.55**	**94.36**	**-1.19**
Pitcher 2	**67.20**	**66.83**	**-0.37**

In summary, the types of control frames and camera setups discussed here seem very appropriate for many artifact types. The results seen above are believed to be adequate for many archaeological purposes when dealing with small artifacts or bones. With calibration of the camera, the results should improve over a much greater range of artifact size. However, it should be noted that if time and/or funding permits, the objects of interest can be photographed with more than one orientation. Through this approach, most “depth” or “thickness” measurements, where the greatest error has been found, can be taken from a planar context resulting in quite accurate results.

D. PRELIMINARY ASSESSMENT OF MEASUREMENTS DEVIATIONS IN X, Y AND Z

Due to the apparent patterning of deviations in the above examples we elected to more formally assess the nature and distribution of deviation provided by the two cameras and assess how these were related to the object size and orientation. The discussion here, therefore, is not intended to replace either a formal calibration process or a rigorous mathematical consideration of the consequences of optical properties of camera and lens combinations. It does serve to provide, however, an accessible and almost intuitive sense for the non-photogrammetrist, of the factors that are in play in the methods under consideration here. It should also provide guidance as to the type and magnitude of limitations that can be placed on effective softcopy mensuration by differing camera systems.

The following discussion will, again, be limited to the two cameras previously discussed (the Nikon and Minolta) and to the use of the vertical control frame setup which consists of a glass plate with pyramid-like vertical controls (figure 16). This frame was chosen since it had - numerous points of vertical and horizontal control. The two stereo pairs used for this measurement testing were shot utilizing the same basic parameters. The camera distance, and placement of control points were identical for both the Nikon and Minolta stereo pairs. The base distance was somewhat different due to the differing focal lengths of the cameras. This analysis allowed us to test the importance of individual cameras and lenses, the accuracy of their resultant measurements and how the depth or z value of artifacts can affect accuracy of measurements from 3-D images.

In order to analyze the error differences between the two cameras, fourteen points were chosen and these same points were measured in both stereo pairs, one pair was taken with the Nikon and one with the Minolta. The points were chosen to vary z values, as well as to insure horizontal distribution across the control field. Two of each of the following elevations were chosen: 0, 10, 16.1, 20, 30,40, and 50mm. These points were also horizontally distributed across the control field from each other. For example, two points at a height of 20 mm were not chosen if they were in close proximity to one another. These points were then measured from the imagery and recorded for x, y (horizontal) and z (depth) values and then compared to the manually measured values in order to derive an error of x, y, and z for each stereo pair. It should be noted that only coordinates of points were considered and not measured distances.

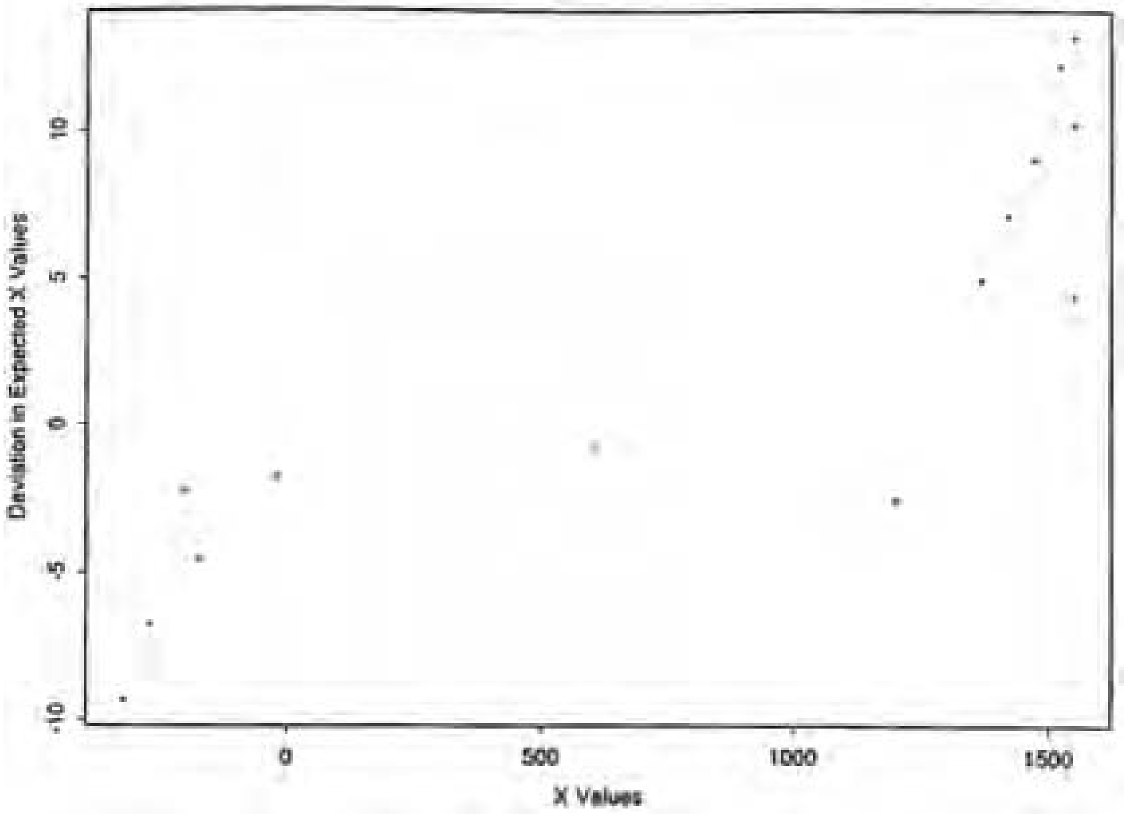
By utilizing this method, one does not put greater emphasis on any single point, rather we are looking at the difference between the manual and digital measurements for varying depth and horizontal placement. The units utilized in the following graphs are 1/10 millimeter. Deviations in any single measurement are the result of a complex geometric interaction between factors such as radial lens distortion, lack of film flatness, and similar processes. As a result, deviations (errors) will occur across the image due to variation in the x-y plane but will also vary due to the location of the portion of the object within the z (or depth) axis. For purposes of simplifying the processes involved, we will present a brief discussion of these deviations as univariate relationships. Our purpose here is not to recapitulate the already voluminous optical and photogrammmetric literature but to provide the archaeologist, museum specialist or other reader with a more intuitive understanding of the impact of these processes on the measurement of objects.

Finally, this discussion is designed to lay some initial groundwork for the development and application of a low cost method for lens calibration and the use of this calibration data to improve the accuracy of future lowcost photgrammetrically derived measurements.

In figures 41,42, 43, and 44 we have plotted the deviations produced by the Minolta camera when used to photograph the 14 points on the control frame (actual coordinates are found in Appendix E). Figure 41 plots the deviations in x as a function of their location on the x-axis, figure 42 shows the deviations in y plotted against their location on the y-axis, figure 43piots the deviations in x values against the z-axis coordinate of the observation while figure 44 plots the y deviations against the z-axis location. While there are exceptions, both x and y deviations generally -follow a similar pattern. Observations taken closer to the center of the images have the smallest deviations while those at greater distances have greater deviations. For example, deviations of -10 are found on the far left of the image while deviations from 5 to 10 are found for the seven observations taken to the far right. A similar pattern is even more obvious in the plot of the deviations against the z-axis. Those locations in the images at the lowest points on the z-axis tend to have the lowest deviations (under 2/10 of a millimeter) and deviations increase as the z-value (height) increases. At a x value of 30 millimeters (300 on the plot) the two x values are 6/10 of a millimeter and more that 1 millimeter. As the z value increases, the location being measured is actually closer to the lens and, in this case, further from the center of the image. While this overall pattern is clear, it is by no means absolute, due to the complex optical interactions noted above. For example, observations at the 16.1 mm z-level have some of the largest deviations in y but have very small deviations in x.

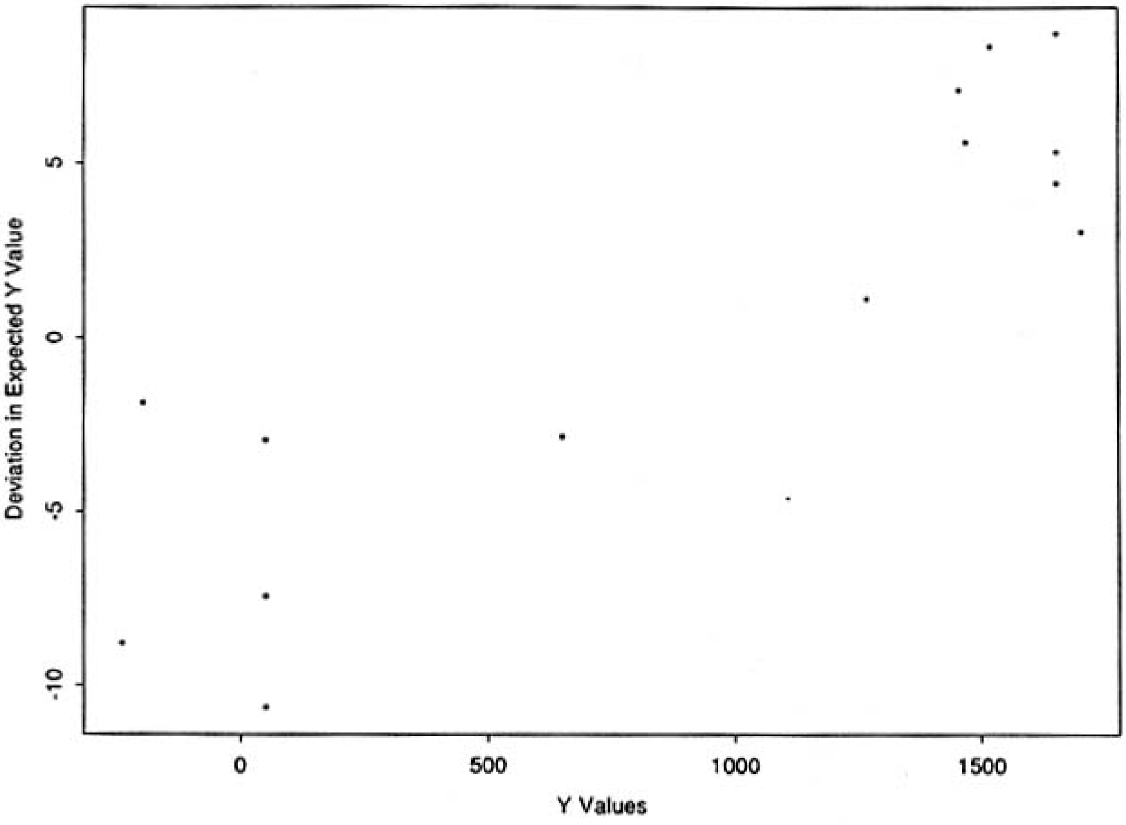
A similar set of plots were prepared for the Nikon and are shown as figures 45,46,47, and 48. The general pattern observed for the Minolta is also found here but the size of the deviations are much smaller and there is only a modest substantive increase in deviations with increasing z-axis values. As we have noted before, and as expected, the optical characteristics of the Nikon camera and its fixed focal length lens provide a superior result. The maximum deviation for the Nikon is only 7/10 of a millimeter and the great majority are under 1/2 of a millimeter.

These results suggest that it will be possible to develop a low cost calibration procedure that can be applied to cameras of the type used here. If this is the case, then it appears quite likely that even the modest deviations encountered in this analysis can be reduced.



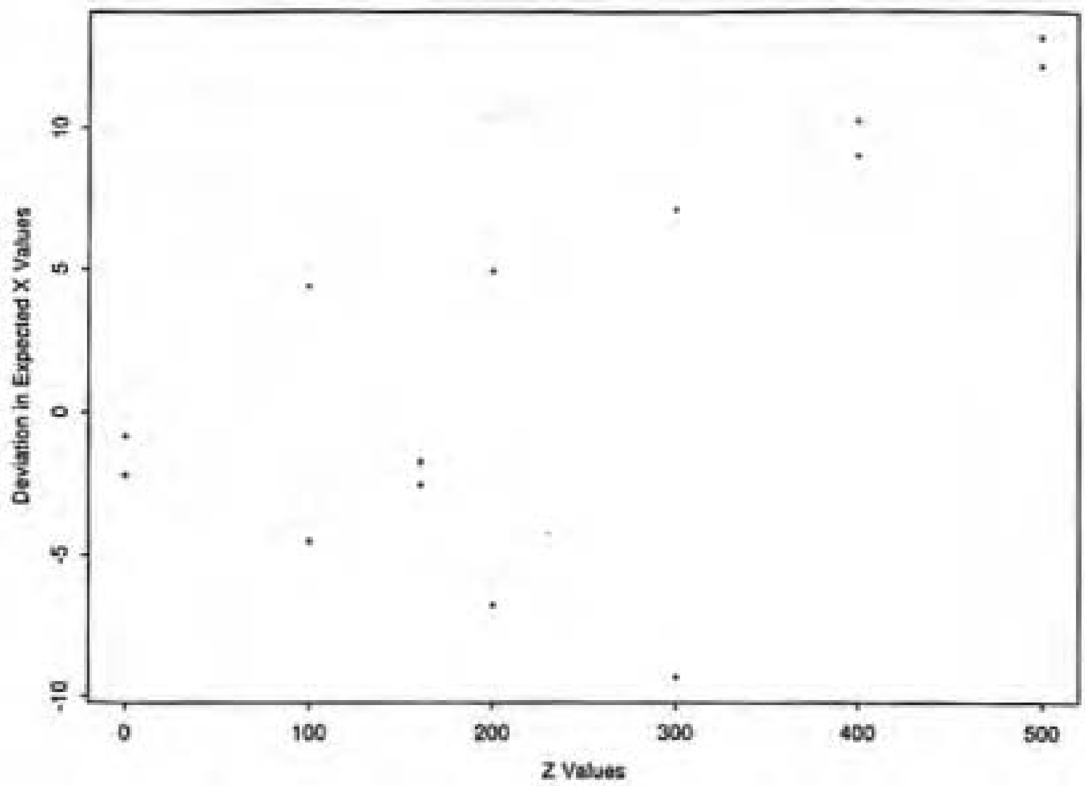
X Values

Figure 41. Deviations in x compared to x (Minolta)



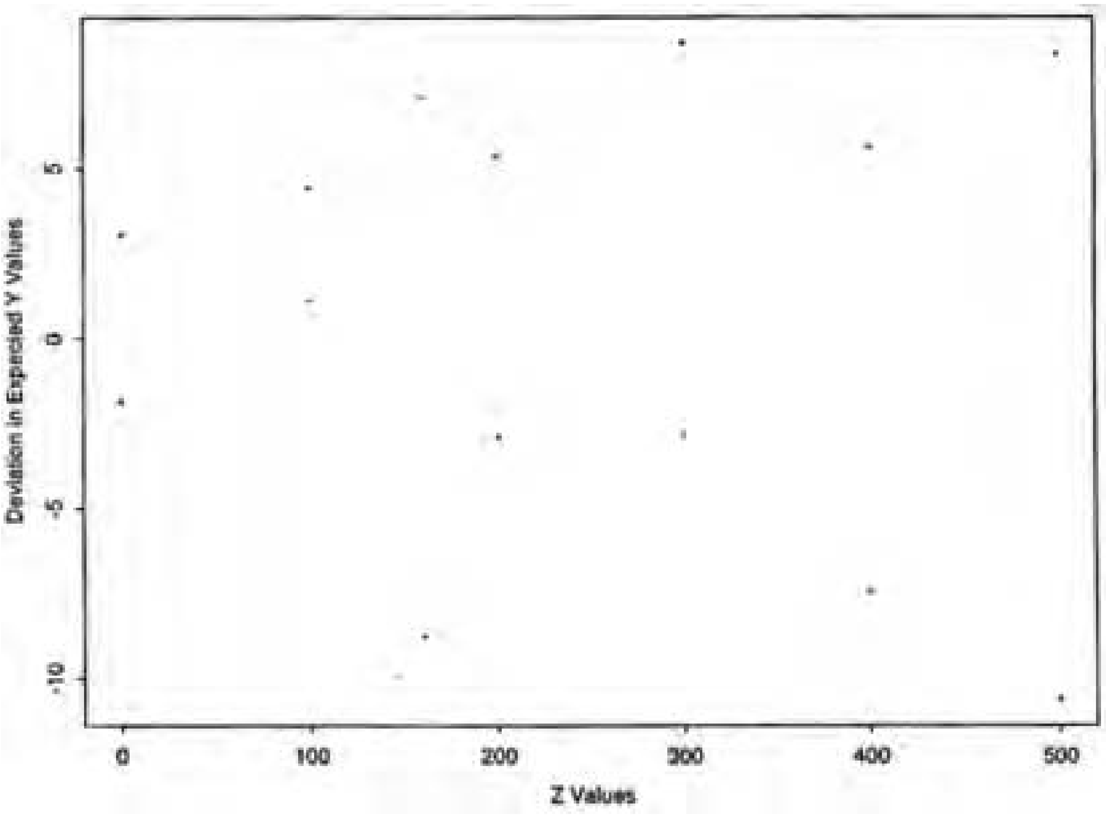
Y Values

Figure 42. Deviations in y compared to y (Minolta)



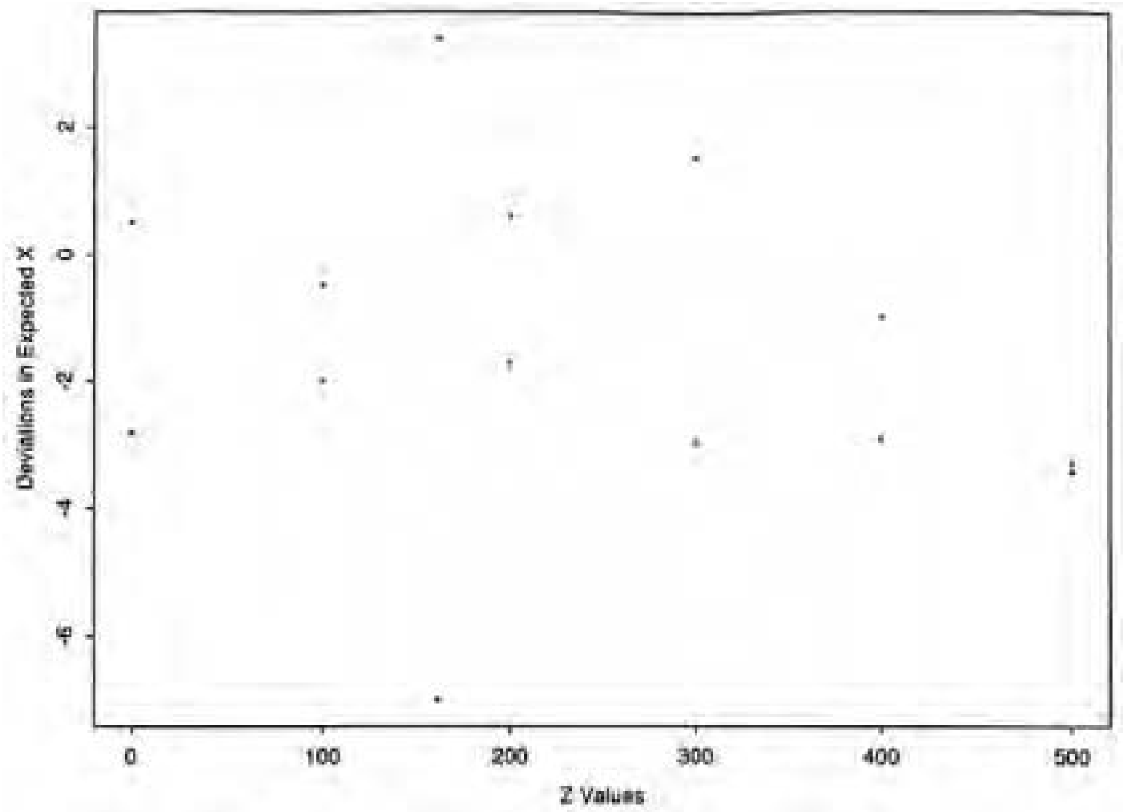
Z Values

Figure 43. Deviations in x compared to z (Minolta)



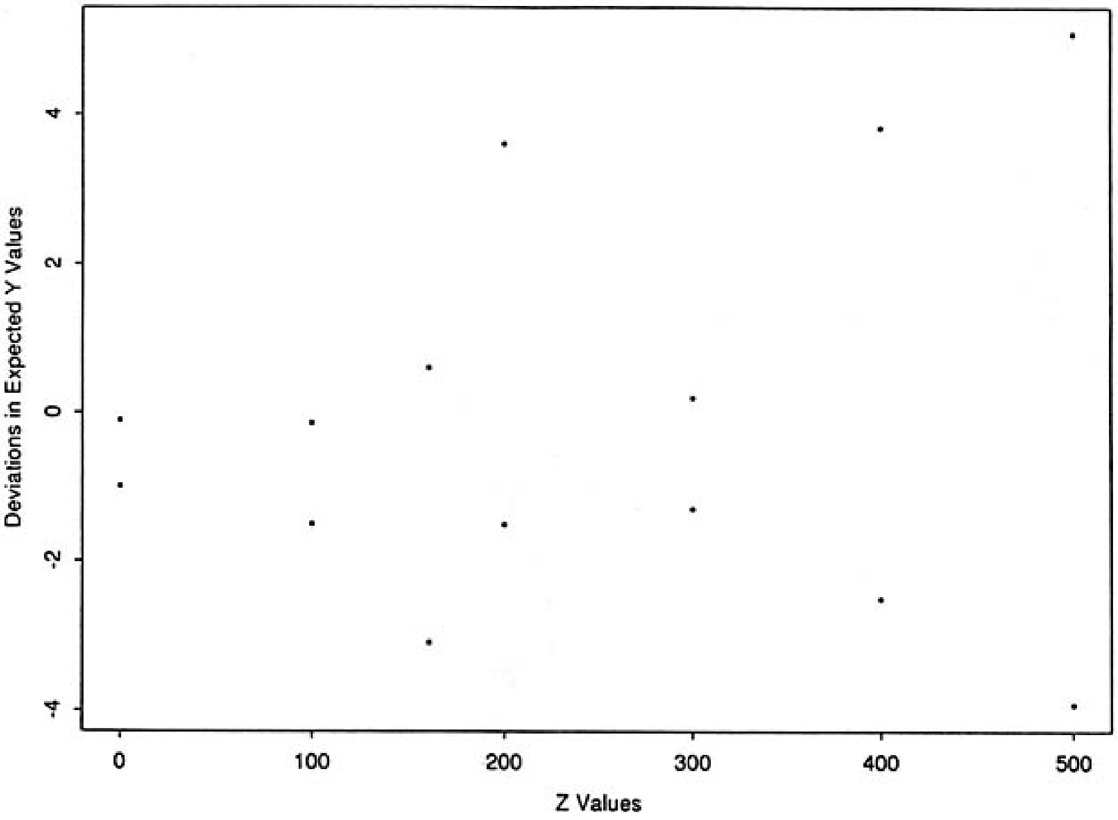
Z Values

Figure 44. Deviations in y compared to z (Minolta)



Z Values

Figure 47. Deviations in x compared to z (Nikon)



Z Values

Figure 48. Deviations in y compared to z (Nikon)

A further assessment of interest is a comparison of the results of “standard” measurements of objects made by multiple individuals compared with the same “standard” measurements using the softcopy photogrammetry. For example, it is likely that the “standard” measurement of the width of a stone knife or the diameter of a pottery vessel will vary slightly from one observer to another because of differences in selection of the point(s) for measurement as well as differences in measurement procedures and precision. A “blind-test” was conducted to assess these differences. Four archeologists were presented with a variety of artifacts and were asked to take and record their measurements of overall length, width, and thickness (height) using vernier calipers. The three principle investigators of this report then performed the same “standard” measurements on the softcopy 3-D images for the same artifacts. The following tables (tables 5 and 6) show the average of the measurements taken by the four archaeologists and the three software operators. Also shown, is the greatest amount of variation between the recorded measurements. For example, if the lowest manual measurement recorded for a specific point was 5 cm and the highest was 10 cm then the greatest variation would be recorded as 5 cm. The actual measurements used to create these tables can be found in Appendix D.

From these tables, one can see that the average manual and softcopy measurements are quite similar, although, there seems to be more variability among manual measurements. The differences between averages obtained for manually and digitally measured values range from 0.18 mm to 10.14 mm (table 11), the latter being the difference for the height of the ceramic pot. If, however, the 10.14mm difference is not figured into this range, it then becomes 0.18 mm to 1.33 mm. This range of differences should be quite acceptable as it does not reflect any more variation than that seen between various individuals when measuring the same artifact feature. In general, there is greater depth variability between the two methods. This is in keeping with the results discussed earlier in this report.

Table 9. Manual Measurements

Artifact Type/Point Measured	Average Measured Value (mm)	Greatest Variation Between Measured Values (mm)
Ceramic Pot		
Height	**95.44**	**2.70**
Width	**127.33**	**1.70**
Rim thickness	**7.83**	**1.50**
Projectile		
Length	**41.56**	**2.25**
Width	**20.35**	**2.10**
Thickness	**5.48**	**1.90**
Adze #1		
Length	**56.14**	**6.20**
Width	**39.71**	**2.90**
Thickness	**16.77**	**6.20**
Adze #2		
Length	**79.92**	**1.30**
Width	**43.11**	**1.95**
Thickness	**18.00**	**2.60**

Table 10. Softcopy Measurements

Artifact Type/Point Measured	Average Measured Value (mm)	Greatest Variation Between Measured Values (mm)
Ceramic Pot		
Height	**85.30**	**1.82**
Width	**126.87**	**0.72**
Rim thickness	**7.39**	**1.47**
Projectile		
Length	**42.04**	**1.46**
Width	**20.62**	**0.70**
Thickness	**6.46**	**0.95**
Adze #1		
Length	**57.47**	**3.04**
Width	**40.62**	**0.99**
Thickness	**17.25**	**0.76**
Adze #2		
Length	**81.20**	**0.69**
Width	**43.29**	**1.08**
Thickness	**18.80**	**1.19**

Table 11. Difference Between Softcopy and Manual Averaged Values

Artifact Type/Point Measured	Average Manually Measured Value (mm)	Average Softcopy Measured Value (mm)	Absolute Difference Between Manual and Softcopy Averages (mm)
Ceramic Pot			
Height	**95.44**	**85.30**	**10.14**
Width	**127.33**	**126.87**	**0.46**
Rim thickness	**7.83**	**7.39**	**0.44**
Projectile			
Length	**41.56**	**42.04**	**0.48**
Width	**20.35**	**20.62**	**0.27**
Thickness	**5.48**	**6.46**	**0.98**
Adze #1			
Length	**56.14**	**57.47**	**1.33**
Width	**39.71**	**40.62**	**0.91**
Thickness	**16.77**	**17.25**	**0.48**
Adze #2			
Length	**79.92**	**81.20**	**1.28**
Width	**43.11**	**43.29**	**0.79**
Thickness	**18.00**	**18.80**	**0.80**

ALTERNATIVE METHODS

While the approach discussed here provides an excellent low cost method to develop measurements from objects, there is an important restriction to be noted. As presented, the methodology does not permit the development of a seamless 3-D representation of an object without substantial additional effort. Because the method outlined here deals with one or more stereo pairs from which measurements can be extracted, these pairs cannot be merged to form a continuous coverage of the object. Such a process would require that any given point on the object have a unique set of coordinates with respect to a single origin. if the artifact is placed within a control frame and then photographed from one angle, rotated and photographed again, the two photographs would present two different faces which would both have the same coordinate structure. In order to generate a unique control field around the artifact without part of the control frame hiding a portion of the object, one needs to define control points located on the object itself and to insure that at least six of them are visible from any angle. The object could then be placed on a rotating table and photographs taken at regular interval. This process would generate a strip of overlapping images which could then be processed to generate a sequence of stereo pairs. Since it has not been tested as part of our study, we can only assume such a method would work. With a softcopy system, one is able to view only one pair a time, therefore one would not be able to directly measure a feature spanning more than one pair. One would be able on the other hand, to view an object’s surface by scrolling through the models. For example, if the body of a vase is recorded on photos one through eight, one would be able to view photos one and two, two and three, three and four, etc. Therefore, a feature running around most of the surface, could be measured as several segments. Photographic techniques are especially important when generating a sequence of stereo pairs. Indeed, in order to measure features spanning several stereo model, edges must be very sharp.

Other considerations must also be addressed regarding the organization and documentation for the resulting data. As explained earlier (see section about documentation) values used for base distance, camera distance, camera interior orientation, and controls must be precisely recorded in order for the stereo pairs to be usable. Such a documentation system is even more important when dealing with multiple stereo pairs. A systematic method to organize the information is therefore necessary. A computerized system would most likely be best, especially if artifact inventories are to be shared over the Internet. A team from City University in London is designing a digital information system which allows a user to view three-dimensional drawings and to interactively access any information relevant to any features selected. Their purpose for creating such a system is to efficiently archive all field notes, historical records and photographs collected while performing a photogrammetric survey of the Tomb of Christ in Jerusalem (Cooper et al., 1992). The tomb, located inside the Church of the Holy Sepulchre, is used by six religious communities and its access and ownership are ruled by several international treaties. Because neglect or poor maintenance are often invoked by one group to gain ownership over another, photogrammetry was chosen to generate an accurate, detailed and reliable record of the condition of the tomb, which can be used to arbitrate any litigation. The total surface of the site was recorded with stereo pairs, and close-up photographs were taken to document the condition of individual stone blocks. The resulting information system consists of the CAD software Microstation, the Oracle database and a graphic interface (Robson et al., 1994). Three-dimensional plans and models of the tomb’s wall and features were generated from the stereo pairs, and entered into the information system along with all the other photographs, archaeological records and historic maps available. All this information was then linked together so as to allow the user to access all the information available about a feature just by selecting it on one of the plans.

Much research is being done to improve the creation of three-dimensional models from stereo pairs. Powerful CAD systems allow the user to generate three-dimensional line drawings which can then be filled so as to simulate their surface, this operation is called rendering. The software product FotoG-FMS by Vexcel, for instance, is based on Microstation graphic capabilities and enables one to generate rendered three-dimensional models from convergent photographs (Graham, 1995). A major advantage is that the digitizing is done on single photos therefore bypassing the need for dynamic stereoviewing and powerful workstations. Rendered models do not show the actual surface of an object and hence would not be completely satisfactory to archive archaeological artifacts. One might expect however, that in the near future one will be able to wrap the actual image over the modelled surface.

CONCLUSION

The method discussed in this report addresses the critical need for a rapid, low cost mean to record archaeological artifacts and osteological materials in a manner that will allow retrieval of metric information at a later time. It is usable by the archaeologist, museum specialist or other reader not trained in photogrammetry. The archiving is done using traditional photographic equipment techniques generating a reliable color photographic record for archaeological collections. Photogrammetry allows the extraction of accurate measurements of these images while the scanning operation enables the transfer of museum record over the Internet -therefore solving the problems involved in locating and transporting artifacts.

The use of 35mm cameras has the advantage that the archiving can be done with standard museum equipment and provides a measurement accuracy suitable for most archival and archaeological work. A low-cost calibration procedure could however greatly enhance the potentials of this method and should be the focus of further research efforts.

At the completion of this study, only the photographic process could be qualified as truly affordable for institutions such as museums and universities. The recent introduction of products such as high-resolution scanners and 3-D liquid-crystal shutter glasses for PCs, indicate that in the near future one will be able to also perform the digital portion of the work at a reasonable cost.

APPENDIX A - SOME IMPORTANT PHOTOGRAPHIC CONCERNS

Photography is a method of recording a visible three-dimensional world in two dimensionsl using light, camera, and film. Photogrammetry refers to the method using a pair of two-dimensional images to reconstruct a three-dimensional model similar to the original world. Any information transfer procedure will result in some loss of data or in the introduction of distortion and noise. To minimize these phenomena, it is important to be familiar with the general concepts of photography.

Light is a stream of massless photons carrying a certain amount of energy forward in a sine - wave fashion along a straight line axis. White light can be broken down in its spectral components, or spectrum. The colors violet, blue, green, yellow, orange and red represent the part of the spectrum which is visible to the human eye. Sunlight is a mix of these colors along with other invisible wavelengths such as utraviolet and infrared. The intensity of light is directly proportional to the number of photons present, and to each photon's amount of energy. Violet photons, for example, have the highest energy while red photons have the lowest.

The color temperature of a light source is indicative of its spectrum distributon. Physics observations tell us that the spectrum of light emitted by a blackbody is dependent on its temperature. The higher temperature of a blackbody, the higher the photon frequency it emits. Various light sources such as flash, tungsten lights are generated by combining different wavelengths. Sun light is ideal for photography in terms of temperature and spectral components. The closer artificial light sources are to sunlight the better they are for photography. Some examples of interest for photographers are listed below:

Table 9. Light sources used in photography

Type of light source	Temperature (in K)
normal direct sunlight or daylight	5500
flash light	5500
sky-scattered sunlight *	6500
tungsten studio flood light	3400

* indirect sun light such as indoor daytime light or outdoor in a shaded area

Color film are designed for three levels of color temperature: 5500K, 3400K and 3200K. Matching the film type used to the temperature of the light source is essential to minimize color distortion. Flash light is very close to sun light and therefore the same film types can be use for both cases .The use of daylight film with tungsten lighting, however, would produce photographs to have a yellowish to reddish color. Tungsten film and daylight, on the other hand, generate a blue to cyanish color. Certain filters, such as the Radon 85 series, can be used to adjust the spectrum of a light source. These can be used to decrease the spectrum, for example when using tungsten film and daylight, or to increase color temperature, when using daylight film and tungsten lights. For more details on this topic, please refer to a photography manual.

Another concept of photography crucial to this study is that of refraction and reflection. These phenomena are especially important when a transparent surface, such as the control frames -used in this study, is photographed. Part of the light rays are propagated through the surface and are deviated or bent in the process, this phenomenon is referred as propagation. The amount of deviation can be minimized if the transparent surface has good optical qualities. Refraction will have a negative impact on the measurements extracted from stereo images if one attempts to measure points which are visible through a transparent surface. Indeed, their position will most likely be inaccurate due to the deviation of light rays. Reflection is the process by which light rays bounce off a smooth surface. Light rays reflected towards the camera can cause a mirror reflection effect which in turn hides part of the surface photographed. Light sources should therefore, be carefully placed and oriented to prevent this phenomenon.

APPENDIX B - TECHNIQUES TO SIMULATE 3-D EFFECT

Most presentations could benefit from a mean to realistically represent data in three dimensions. Stereoviewing and holograms for example, are two well known techniques. Stereo pairs provide a natural way to recreate the perception of depth. These can be viewed without any instruments with a little bit of training by focussing each eye on its corresponding image. Since it is a non-trivial exercise which would not be very effective in the context of a group of individuals, several mechanisms are provided to assist the viewer.

1. Binoculars and stereoscopes

Binoculars or stereoscopes can be used to help one focus each eye on the correponding image. if viewed on a computer, the overlapping area of the two images are displayed side by side.

2. Anaglyphic filters

This fairly common method consists in taking a stereo pair of gray-scale stereo images and in displaying them on top of each other using different filters. Glasses with complementary filters are then used to view the images. This process is another method to assist the left and right eyes to focus on their corresponding image only. Inexpensive glasses commonly available for this purpose use a red and a blue filters for the left and right eye respectively. The left and right image must therefore been displayed with a blue and red filter respectively. This system is easy and inexpensive to use, however it does not allow for the viewing of most color images, nor does it allow one to obtain any kind of precise measurements for the elevation. This technique has however, the advantage that it can be used on any color media including slides and computer displays.

3. Polarized glasses

This method is restricted to cathod ray tube (CRT) displays such as computer screens. Two stereo photographs are displayed sequentially at 60Mhz, liquid crystal shutter glasses are used in synchronization to allow the right eye to see only when the right image is displayed, and the left eye to see only when the left image is displayed. This viewing system is fully integrated with the software allowing continuous reading of the cursor's x, y, z location during the dynamic roaming of a stereo model. Such a system allows one to derive very precise measurements or to digitize features. While such a system is very computation-intensive, it has the irreplaceable capability to faithfully display high-quality color images. This technology has recently been extended to liquid crystal display (LCD) projectors allowing the projection of three-dimensional data in the context of a meeting or presentation.

Among methods to generate a three-dimensional effect without using stereo pairs, a simple and inexpensive one uses the process of Chromadepth(TM) 3-D to "encode depth into an image by means of color, then decode the colors by means of optics producing the depth perception" (Toutin and Rivard, 1995: 1210). Toutin and Rivard used this method to generate an elevation map which can be viewed three-dimensionally using clear inexpensive glasses which "act like thick glass prisms" (1995: 1210). When viewed through the glasses, colored areas appear to be at different depth based on the position of the color in the electromagnetic waves spectrum. Areas in red for example, appear higher than those in blue.

APPENDIX C - C PROGRAM GENERATING DATA FOR THE PHOTOGRAPHIC SETUP

```
/*
**   This C program is for calculating the image distance (Di), object distance (Do),
**  the distance to be added to the frame (d), and the correponding k factor
**  based on the control frame size, and
**   the focal length of the camera lens. t[j] is the depth or
**  thickness of the control frame or artifact and w[j] are the widths of the
**  control frame. This will need to be edited below and then run to retrieve the
**  various camera distances and base distances for your projects.
**Enter the desired focal lengths (f), artifact/control frame height (t), and control frame width
**(w).
**  The formulas used in this program are:
**

**  f*squ(d) + (1.052wf-18t+21.6f)*d -1.053*18wt = 0
**  d = (-b + squr(squ(b) - 4ac)) / (2a)
**  where a=f, b=1.052wf-18t+21.6f, and c= -l.053*18wt
**
**  then v=18t/d, u=l8tf/(18t-df), and k=(1.053w+d)/w
**
**  the factor 1.053, comes from condisdering 95% coverage of camera
**  view finder.
**
**  the d, v, and u calculation is the solution of the following equation
**  group:
**   l/f=l/v + l/u
**d = 18t/v
**  l.053w + d = 0.6 * 36u/v
**
*/

#include <stdio.h>
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <fcntl.h>
#include <math.h>



main()
{
int  f[3],  t[4],  w{4],  i,  j;
double  u,  v,  a,  b,  c,  d,  k;
i = j = 0;
```

```
u=v=a=b=c=d=k=0;

**  enter the desired focal lengths, artifact depth and
frame width in the following fields.
**  after editing this file (1) enter: gcc –o calc
file_name –in (2) enter: calc | file or printer

f[0]=28;
f[1]=70;
f[2]=210;
t[0]=25;
t[1]=50;
t[2]=l00;
t[3]=200;
w{0]=l00;
w{1]=300;
w[2]=300;
w[3]=400;


for(i=0;  i<3;  i++)
 {
 printf(“\nWhen focal length f=%dmm, \n\n”, f[i]);
 printf(“ Df Wf Di Do d k\n\n”);


 for(j=0;  j<4;  j++)
 {
 a=f[I];
 b=1.053*w[j]*f[i]+21.6*f[i]-18*t[j];
 c.= -1.053*18*w[j]*t[j];
 d= (–b+sqrt (b*b–4*a*c) ) / (2*a);
 v= (18*t [j]) /d;
 u=18*f[I]*t[j] / (18*t[j]–f[i]*d);
 k= (1.053*w[j]+d) / w[j];
 printf (“%4d  %5d  %9.2lf  %9.21f  %9.2lf  %9.21f\n\n”,
t[j],  w[j],  v,  u,  d,  k);
 }
 }
}
```

APPENDIX D - DATA COLLECTED DURING THE "BLIND) TEST"

Table 10. Manual Measurements by Archaeologists

Artifact Type/Point Measured	Arch. #1	Arch. #2	Arch. #3	Arch. #4
Ceramic Pot				
Height	94.85	94.1	96.0	96.8
Width	127.0	127.0	128.5	126.8
Rim thickness	7.3	7.0	8.5	8.5
Projectile				
Length	40.25	41.0	42.5	42.5
Width	19.4	19.5	21.5	21.0
Thickness	4.05	4.5	5.5	5.95
Adze #1				
Length	56.35	52.0	58.0	58.2
Width	39.95	38.0	40.0	40.9
Thickness	12.7	17.0	18.5	18.9
Adze #2				
Length	79.2	80.0	80.0	80.5
Width	42.25	42.50	43.5	44.2
Thickness	17.4	16.5	19.0	19.1

Table 11. Digital Measurements by Software Operators

Artifact Type/Point Measured	Operator #1	Operator #2	Operator #3
Ceramic Pot			
Height of Pot (depth or z value)	84.68	84.73	86.5
Width	127.10	127.12	126.40
Rim thickness	8.27	7.11	6.80
Projectile			
Length	41.48	42.94	41.69
Width	20.30	20.56	21.0
Thickness	6.87	5.92	6.59
Adze #1			
Length	57.38	59.04	56.0
Width	40.87	40.99	40.0
Thickness	16.99	17.75	17.0
Adze #2			
Length	80.85	81.54	81.2
Width	43.39	43.78	42.7
Thickness	17.91	19.04	19.1

APPENDIX E - DATA TO ASSESS DEVIATIONS IN X, Y and Z

Table 12. Measurements along the X axis (for the Minolta and the Nikon cameras)

Manually Measured X Value (mm)	Digitally Measured Minolta X Value (mm)	Digitally Measured Nikon X Value (mm)
-32.000	-31.069	-32.150
-27 .000	-26.320	-27 .059
-20.000	-19.778	-20.050
-17.000	-16.547	-16.949
-1.990	-1.812	-2.330
60.000	60.086	60.280
120.400	120.659	121.100
137.000	136.509	137. 170
142.000	141.291	142.297
147.000	146.099	147.292
152.000	150.778	152.330
155.000	154.561	155.200
155.000	153.977	155.100
155.000	153.677	155.344

Table 13. Measurements along the Y axis (for the Minolta and the Nikon cameras

Manually Measured Y Value (mm)	Digitally Measured Minolta Y Value (mm)	Digitally Measured Nikon Y Value (mm)
-24.200	-23 .321	-23.890
-20.000	-19.813	-19.990
5.000	5.293	4.640
5.000	5.744	4.618
5.000	6.063	4.490
65.000	65.284	64.981
127.000	126.890	127.150
145.700	144.990	145.640
147.000	146.441	147.250
1520.00	1511.63	152.392
165.000	164.558	1650.14
165.000	164.467	165.152
165.000	164.124	165.130
170.000	169.696	170.100

Table 14. Measurements along the Z axis (for the Minolta and the Nikon cameras)

Manually Measured Z Value (mm)	Digitally Measured Minolta Z Value (mm)	Digitally Measured Nikon Z Value (mm)
0.00	-2.688	1.297
0.00	-5.944	2.560
10.000	7.597	11.697
10.000	6.776	11.090
16. 100	16.346	15.490
16. 100	14.417	16.540
20.000	19.892	20.407
20.000	20.65 1	19.490
30.000	32.590	29.260
30.000	3 1.859	28.867
40.000	44.797	37 .050
40.000	44.593	38.030
50.000	58.708	45.090
50.000	57.368	46.576

APPENDIX F - A HELPFUL CHECK LIST

The following is a list of the key points which one should remember prior to starting a photographic session.

Control frame

- control points should be measured, labelled, and recorded prior to the shooting
- if some controls are not permanently fixed, one should ensure that they will not shift - during the photography session

Artifacts

- collections to be recorded should be organized so as to ease the shooting e.g. by size, proveniance, or by control frame used
- cards or labels should be prepared to indicate proveniance, assession number, etc.

Photographic setup

- select a control frame
- compute camera and base distance to generate a 60% overlap
- setup a light background behind the control frame which will fill the whole area photographed (this can be tested by checking through the viewfinder that all corners are well lit and clearly visible for the left and right camera positions)
- After setting up the lighting system, insure that shadow or reflection do not hide control points or important features
- check that the edges of each artifact are well defined and not blended with either shadow or the background

Documentation

- make sure that all information pertinent to the photographic setup has been recorded and will be stored with the processed images e.g. camera distance, base distance, coordinates of the control points
- a shooting record (see appendix G) should be filled for each roll of film as artifacts, camera position, focal length or other parameters are changed.

Close Range Photogrammetry Shooting Record

- Location _______________, Shoot # ________, Date: 19 - _____ -- _____- _____;
- Camera: ____________________________, Series No. _________________
- Lens: _________________________, Series No. __________________
- Film: ______________________, Speed_____ASA/DIN, Clr/BW, Sid/Neg, Daylight/Tungsten, Ex. date: 19 -_____- _____.

Ex #	**Film #**	**Pair #**	**Object**	**Dc**	**Do**	**Ad**	**Db**	**Speed**	**Apert.**	**Focal Length**	**Others**
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											
16											

GLOSSARY

Absolute orientation;

The scaling, leveling, and orientation to control points of a relatively oriented stereoscopic model or group of models (Terrazas, 1986: 216).

Accuracy;

"The degree of conformity with a standard, or degree of perfection attained in a measurement. Accuracy relates to the quality of a result, and is distinguished from precision which relates to the quality of the operation by which the result is obtained" (Terrazas, 1986: 122).

Aerial photogrammetry:

Photogrammetry utilizing aerial (vertical or oblique) photographs.

Air base (or in the context of this project, base distance):

The distance between the camera positions at which the left and right stereo images are taken.

Affine transformation:

A mathematical operation used to modify a two-dimensional surface. It is characterized by the fact that, unlike the conformal model, it applies different scaling to the x and y axes. This transformation requires four points to reach a solution. If at least one more point is used, a better solution can be obtained with the least squares adjustment method (Wolf, 1983: 584).

Analogue stereoplotter:

A stereoplotter implementing all orientations and corrections with optical and mechanical means.

Analytical photogrammetry:

Photogrammetry in which orientations and corrections are performed mathematically rather than with mechanical and optical means.

Analytical stereoplotter:

It "is a stereo comparator, encoded so that coordinate measurements on photographs can be passed to a computer and converted into digital form." (Warner, 1990 : 571 from Koency G. 1980). Contours and features are digitized off the hardcopies and plotted out from the computer.

Base Distance (close-range equivalent of air base):

For the purpose of this project, we refer to the distance between the two camera positions at which the left and right stereo images are taken, as the base distance.

Base-height ratio (B:H):

Term used for stereo images referring to the ratio between the air base (base distance) and the flying height (camera distance). A recommended value is 1:6.

Byte:

Unit used to express the size of digital data. Typically, one character occupies one byte of digital storage.

Calibrated focal length:

"An adjusted value of the equivalent focal length so computed as to distribute the effect of lens distortion in a desired manner over the entire field used in a camera" (Terrazas, 1986: 99).

Camera calibration:

"The determination of the calibrated focal length, the location of the principal point with respect to the fiducial marks, the point of symmetry, the resolution of the lens, the degree of flatness of the focal plane, and the lens distortion effective in the focal plane of the camera and referred to the particular calibrated focal length" (Terrazas, 1986:35).

Camera distance (close-range equivalent of flying height):

For the purpose of this project, we refer to the distance between the film plane and the average depth of the object or area photographed as camera distance.

Check point:

Points of known three-dimensional coordinates and visible on both stereo images which are used to assess the quality of the absolute orientation solution.

Close-range photogrammetry:

It applies to terrestrial photogrammetric applications for which the camera-object distance is less than three hundred meters (Wolf, 1983: 477).

Conformal transformation:

A mathematical operation used to modify a two-dimensional surface. It is characterized by the fact that it applies the same transformation to the x and y axes i.e. it preserves a surface's proportions. This transformation requires two points to reach a solution. If at least one more point is used, a better solution can be obtained with the least squares adjustment method (Wolf, 1983: 576).

Contour line:

A line on a map or photograph joining points of equal values for a continuous phenomenon such as elevation.

Control field (frame):

In order to obtain accurate measurements from a stereo pair, one needs to have at least six control points located on or around the object recorded. Each one of these points must have known three-dimensional coordinates with respect to a single origin. These points then define a three-dimensional reference system to which the object or feature being photographed can be related.

Control point:

Points of known three-dimensional coordinates and visible on both stereo images which are used to perform the absolute orientation.

Convergent/monoscopic photogrammetry:

It is characterized by the use of two or more cameras positioned at an angle converging towards the object of interest. Although it does not allow the three-dimensional viewing of a stereo pair, this method is considered more versatile and more accurate than stereo-photogrammetry and is used primarily for industrial applications.

Coordinates:

Values which indicate the location of a point with respect to a chosen system or frame of reference.

Cursor:

(on computers) A point displayed on the computer screen which indicates position and can be moved around using a pointing device such as a mouse, stylus or puck.

(on digitizer) A hand-held device with a cross hair or other reference mark for recording position on a digitizer or digital tablet. (Terrazas, 1986: 77).

Digital Elevation Model (DEM):

A matrix (rows and columns) of elevations at even ground spacings.

Digital Terrain Model:

"A digital representation of the terrain in several forms:

Contours: polylines (vectors) representing constant elevations.

Digital Elevation Model (DEM): a matrix (rows and columns) of elevations at even ground spacings.

Triangulated Irregular Network (TIN): a model of the terrain using points which form the vertices of a net of triangles

Can include "breaklines", which define the geomorphology of the terrain by tracing ridges, valleys, rivers, roads, etc. that force contours to cross at right angles to lines" (Molander and Hoffman, 1995).

Digitizer:

A computer-based system to convert point, line and area features from a hardcopy to a digital format.

Distortions:

Lens aberrations affecting the one-to-one correspondence between a feature and its representation on a photograph.

"The most important ones are radial (symmetric) and decentering lens distortions... While these distortions are unique for individual lens, and thus occur in both metric and non-metric cameras, their amounts are often kept negligible by design for metric cameras. In addition to commonly large distortions, the situation for non-metric cameras is further complicated by focusing changes which result in change in these distortions" (Faig, 1989: 72)

Emulsion:

A suspension of either light-sensitive silver salts, diazos, or photopolymers, in a colloidal medium which is used for coating photographic film, plates and papers (Terrazas, 1986: 106).

Exposure:

The act of exposing a sensitized photographic material to a light source.

Fiducial marks:

Four or eight marks etched on the focal plane - in the corners and in the middle of the edges- which are imprinted on the negative at the time of exposure.

Film base:

A thin, flexible, transparent sheet of stable plastic material to which a light-sensitive emulsion may be applied (Terrazas, 1986 :288).

Floating mark:

“A mark seen as occupying a position in the three-dimensional space formed by the stereoscopic fusion of a pair of photographs and used as a reference mark in examining or measuring the stereoscopic model” (Terrazas, 1986: 146).

Flying height (or in the context of this project, camera distance):

The distance between the aircraft and the average terrain elevation of the area photographed is called flying height.

Focal length:

“The distance from the plane of infinite focus to the center of a thin lens (Wolf, 1983: 30).

Focal plane:

“[T]he plane in which all incident light rays are brought to focus (Wolf, 1983: 70).

Gigabyte (Gb):

One gigabyte represents one thousand megabytes.

Interior orientation:

“The determining of the interior perspective of the photograph as it was at the instant of exposure. Elements of interior orientation are the calibrated focal length, location of the calibrated principal point, and the calibrated lens distortion” (Terrazas, 1986: 216).

Kilobyte (Kb):

One kilobyte represents one thousand bytes.

Least squares adjustment:

“Least squares is a procedure for adjusting observations containing random errors... [M]ost probable values of the unknowns can be determined by the method of least squares” (Wolf, 1983: 564). This is achieved using redundant observations.

Megabyte (Mb):

One megabyte represents one million bytes or one thousand kilobytes.

Non-metric and semi-metric cameras:

“A non-metric camera is a camera whose interior orientation is completely or partially unknown and frequently unstable... A metric camera, on the other hand is characterized by a stable, known, and repeatable interior orientation, defined by fiducial marks;.., a semi-metric camera falls somewhere in between.” (Faig, 1989 : 71)

Orthoimage:

“A digital orthophoto in which the effects of terrain and geometry of the photograph are removed to produce a plan view (orthographic projection) of the image” (Molander and Hoffman, 1995).

Overlap:

Area covered by two photographs taken in a sequence.

Photogrammetry:

“Photogrammetry is defined by the American Society of Photogrammetry as the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of recorded radiant electromagnetic energy and other phenomena. (Wolf, 1983: 1)”

Pixel:

A picture element data with assigned intensities representing grey shades (monochromatic) or colors. (Molander and Hoffman, 1995)

Rectification:

“The process of projecting s tilted or oblique photograph onto a horizontal reference plane” (Terrazas, 1986: 270).

Relative orientation:

“The determining of the position and attitude of one of a pair of overlapping photographs with respect to the other photograph” (Terrazas, 1986: 216).

Reseau plate:

A plate on which a grid or cross hairs have been etched and precisely measured. It is placed on the focal plane to provide more fiducial-like points which can be used as part of the interior orientation to correct for film unflatness.

Residual:

“The difference between any measured quantity and the most probable value for that quantity (Wolf, 1983: 560).

Resolution of a digital image:

The size of the sensors used to gather the digital information dictates the density of information actually recorded. Resolution is an indicator of this density. A slide scanned at a resolution 15 micrometers will be stored as a table or matrix where each cell represents an area of 15 x 15 micrometers. Similarly, a 400dpi scanner transforms a hardcopy image into a grid of cells or pixels, each representing a 1/400 x 1/400 of an inch. In the same fashion, a 30 meter satellite image is one where each pixel represents a 30 x 30 meter area on the ground.

Scanner:

A scanner allows the transfer of a hardcopy image into digital form. The scanning head consists of charge coupled devices (CCD) or sensors rectangular in shape which are moved over the image and measure for each portion they stop over the amount of red, green or blue. The highest resolution of a scanner is determined by the size of each CCD. Those used to scan aerial photographic films have CCD as small as 7.5 micrometers. Office-grade scanners typically have a resolution of 600 dots per inch or 40 micrometers.

Softcopy photogrammetry

The field of softcopy photogrammetry was initiated in the 80’s and is dedicated to the photogrammetry process of digital images. It addresses issues such as the gathering of data digitally, the scanning of photographic transparencies, as well as those pertaining to a fully computer-based photogrammetric process.

Standard deviation or Root Mean Square Error (RMSE):

“A quantity used to express the precision of a group of measurements (Wolf, 1983: 561)”. It is expressed as follows:

$$RMSE = \sqrt{\frac{\sum r^2}{d}}$$

where r stands for the residuals and d for the number of degrees of freedom.

Stereocomparator
A stereoscopic instrument for measuring parallax; usually includes a means of measuring photograph coordinates of image points (Terrazas, 1986: 120).

Stereo pair:
A pair of images which are digitally re-sampled to produce a clear stereoscopic model. Each line in the image is an “epipolar” line in which a separation in pixels between two images yields a change in depth in the stereomodel. (Molander and Hoffman, 1995)

Stereo-photogrammetry:
Stereo-photogrammetry is based on the concept of stereo-viewing, which derives from the fact that human beings naturally view their environment in three dimensions. Each eye sees a sin gle scene from slightly different positions. The brain then “calculates” the difference and “reports” the third dimension.

Stereoscope:
“A binocular optical instrument for helping an observer to view photographs, or diagrams, to obtain the mental impression of a three-dimensional model. The design of stereoscopic instruments use a combination of lenses, mirrors and prisms” (Terrazas, 1986: 121).

Strip of stereo photographs:
A series of overlapping photographs taken while moving the camera in one direction and at regular intervals so as to generate a sequence of stereo images.

Stereoplotter:
“An instrument for plotting a map or obtaining spatial solutions by observation of pairs of stereo photographs” (Terrazas, 1986: 29).

Target:
“The distinctive marking or instrumentation of a ground point to aid in its identification on a photograph (Terrazas, 1986: 213).

Terrestrial photogrammetry:
Photograrrimetry applied to non-aerial applications is called terrestrial.

Traditional photogrammetry
“The use of film photography (usually diapositives) with analogue or analytical stereo plotters.” (Molander and Hoffman, *1995)*

REFERENCES

Avery, T. E. and G. L. Berlin

1985 *Fundamentals of Remote Sensing and Airphoto Interpretation.* Macmillan Publishing Company, New York.

Adams, L. P.

1989 Industrial Photogrammetry. In *Non-Topographic Photogrammetry,* edited by H.M. Karara, Chapter 20, pp 349-358. American Society for Photogrammetry and Remote Sensing, Falls Church, Virginia.

Adams, L. P. and A. M. Tregidga

1992 Precise Biological Surface Measurements in Some Medical and Dental Studies. *International Archives of Photogrammetry and Remote Sensing* 29(5):844-849. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Alpers, J.

1995 3D Frequently Asked Questions. Document available under the World Wide Web home page: http://www.tisco.com/3d-web/3dfaq.html

Azarpay, G.

1990 A Photogrammetric Study of Three Gudea Statues. *Journal of the American Oriental Society* 110 (Oct/Dec):660-665.

Baj E., M. Rampolli and G. Bozzolato

1992 Analytical Photogrammetric Survey of the Leaning Tower of Pisa. *International Archives of Photogrammetry and Remote Sensing* 29(5): 174-181. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Baribeau, R.

1993 Range Sensing for the Monitoring of Three-Dimensional Changes. In *Computer Technology for Conservators - the 2nd wave,* edited by Rob Stevenson, pp. 43-49. Atlantic Regional Group of the International Institute for Conservation of Historic and Artistic Works-Canadian Group.

Baribeau,R., M.Rioux and G.Godin

1992 Recent Advances in the Use of a Laser Scanner in the Examination of Paintings. In *Restoration'92 Conservation, training, materials and techniques. latest developments,* edited by Victoria Todd et al., pp 69-73.

Birardi, G.

1992 The "Aerial" Triangulation and the Plotting of the External Walls of Coliseum in Rome. *International Archives of Photogrammetry and Remote Sensing* 29(5):333-341. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Boulianne, M., L. Cloutier and A. K. Ghosh

1991 Cerebral Biopsies Using a Photogrammetric Probe Simulator. *Photogrammetric Engineering and Remote Sensing* 57(10): 1347-1354.

Burns, J. A.
1991 CAD-Photogrammetry: A Powerful Documentation Tool. *CRM* 14(3)4-5.

Carbonnell, M.
1989 Architectural Photogrammetry. In *Non-Topographic Photogrammetry,* edited by H.M. Karara, Chapter 19, pp 321-347. American Society for Photogrammetry and Remote Sensing, Falls Church, Virginia.

Coblenz, A., R. Mollard and G. Ignazi
1991 Three-Dimensional Face Shape Analysis of French Adults, and its Application to the Design of Protective Equipment. *Ergonomics* 34(4):497-5 17.

Cooper, M. A. R., S. Robson and R. M. Littleworth
1992 The Tomb of Christ, Jerusalem; Analytical Photogrammetry and 3D Computer Modelling for Archaeology and Restoration. *International Archives of Photogrammetry and Remote Sensing* 29(5):778-785. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Dallas, R. W. A. and M. Carbonnell
1992 World Heritage Sites - Photogrammetric Records. *International Archives of Photogrammetry and Remote Sensing 29(5):419-426.* American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Donnelly, B. E.
1988 *Film Flatness in 35 mm Cameras.* Master of Surveying Thesis, University of Newcastle, England.

Donnelly, B. E. and J. G. Fryer
1989 Film Unflatness and Small Format Photogrammetry. *Australian Journal of Geodesy, Photogrammetry, and Surveying* 51:57-71.

Eiteljorg, H
1994 Autocad Single-Photo Photogrammetry at Pompeii. *CSA Newsletter - A Quaterly Newsletter for Architectural Historians and Archaeologists* 7(3):3-5

Faig, W., F. R. Wilson, D. King, and T. Y. Shih
1992 Photogrammetric Solution for Vehicle-Damage Investigation. *Journal of Transportation Engineering* 118 (Nov./Dec.): 850-65.

1989 Non-Metric and Semi-Metric Cameras: Data Reduction. In *Non-Topographic Photogrammetry,* edited by H.M. Karara, Chapter 6, pp 7 1-79. American Society for Photogrammetry and Remote Sensing, Falls Church, Virginia.

Fraser, C. S.
1992 Photogrammetric Measurement to One Part in a Million. *Photogrammetric Engineering and Remote Sensing* 58(3): 305-3 10.

Fryer, J. G.

1992 Recent Developments in Camera Calibration for Close-Range Applications. *International Archives of Photogrammetry and Remote Sensing* 29(5):594-599. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

1989 Camera Calibration in Non-Topographic Photogrammetry. In *Non-Topographic Photogrammetry,* edited by H.M. Karara, Chapter *5,* pp 32 1-347. American Society for Photogrammetry and Remote Sensing, Falls Church, Virginia.

Fryer, J. G. and C. S. Fraser

1986 On the Calibration of Underwater Cameras. *Photogrammetric Record* 12(67): 73-85.

Fryer J. G., H. T. Kniest and B. E. Donnelly

1990 Radial Lens Distortion and Film Unflatness in 35mm Cameras. *Australian Journal of Geodesy, Photogrammetry, and Surveying* 53:15-28.

Fryer J. G. and H. L. Mitchell

1987 Radial Distortion and Close-Range Stereophotogrammetry. *Australian Journal of Geodesy, Photogrammetry, and Surveying* 46/47:123-138.

Fussell, A.

1982 Terrestrial Photogrammetry in Archaeology. *World Archaeology* 14(2): 157-172.

Garrison, E. G.

1992 Recent Advances in Close Range Photogrammetry for Underwater Historical Archaeology. *Historical Archaeology.* 26:97-104.

Graham, J.

1995 Down to the Desktop: a New Approach Simplifies the Creation of As-Built Drawings. *MicroStation World.* Winter: 47-48

Gutu, A.

1992 An Architectural Photogrammetric Application: Survey of the Church within Snagov Monastery, Romania. *International Archives of Photogrammetry and Remote Sensing* 29(5):402-408. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Harp, E. Jr. (editor)

1975 *Photography in Archaeological Research.* University of New Mexico Press, Albuquerque.

Helming, K.

1992 Surface Reconstruction and Change Detection for Agricultural Purposes by Close Range Photogrammetry. *International Archives of Photogrammetry and Remote Sensing* 29(5):610-617. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Husen, B. and Benter, U.

1992 Precise Tool Measurement Using Digital Photogrammetry. *International Archives of Photogrammetry and Remote Sensing* 29(5):528-532. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Kempa, M.

1992 Monitoring the Weathering of Stones: Setup and First Results. *International Archives of Photogrammetry and Remote Sensing* 29(5): 292-297. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Kempa M. and M. Schlüter

1992 Graphical Representation of an Armenian Castle with AUTOCAD. *International Archives of Photogrammetry and Remote Sensing* 29(5):241-244. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

King, B. A.

1991 A Relative Orientation for Motor Vehicle Accident Photogrammetry. *Photogrammetric Record* 13(78): 893-899.

Koency, G.

1980 How the Analytical Plotter Works and Differs from an Analog Plotter. *Proceedings of Analytical Plotter Symposium and Workshop*, pp 3 1-75. American Society for Photogrammetry and Remote Sensing. Falls Church, VA.

Mendonça, F. J. B.

1992 Combination Close-Range and Digital Processing in Archaeology. *International Archives of Photogrammetry and Remote Sensing* 29(5):130-132. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Molander, C. W. and G. Hoffman

1995 Softcopy Production. Practical Workshops on Digital Photogrammetry and Imagery Applications. American Society for Photogrammetry and Remote Sensing Regional Workshop Program St. Louis Region.

Novak, K.

1992 Rectification of Digital Imagery. *Photogrammetric Engineering & Remote Sensing* 58(3) 339-344.

Petersen, A.

1992 Metrology Norway System - An On-Line Industrial Photogrammetry System. *International Archives of Photogrammetry and Remote Sensing* 29(5):43-49. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Potsiou C., C. Ioannidis and J. Badekas

1992 A Special Information System for the Documentation of Castles. *International Archives of Photogrammetry and Remote Sensing* 29(5):287-291. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Robson, S., R. M. Littleworth and M. A. R. Cooper

1994 Construction of Accurate 3D Computer Models for Archaeology, Exemplified by a Photogrammetric Survey of the Tomb of Christ in Jerusalem. *International Archives of Photogrammetry*. Melbourne. 30(5):338-344.

Scott, P. J.

1982 Drawing and Measurement of Finds: a Reflex Action. *World Archaeology* 4(2):191-199.

Terrazas, A.

1986 *Glossary of Cartographic and Photogrammetric Terms.* Publication No. 413. Instituto Panamericano de Geografia e Historia, Mexico.

Toutin, T. and B. Rivard

1995 A New Tool for Depth Perception of Multi-Source Data. *Photogrammetric Engineering and Remote Sensing* 61(10): 1209-1211.

Warner, W. S.

1990 A PC-Based Analytical Stereoplotter for Wetland Inventories: An Efficient and Economical Photogrammetric Instrument for Field Offices. *Forest Ecology and Management* 33/34: 57 1-581.

1988 Multi-Use Characteristics of Norwegian Clearcuts: Using Aerial Photographs to Digitize in Three Dimensions, *Scand. Journal For. Res.* (3):401-416.

Warner W. S. and W. W. Carson

1991 Improving Interior Orientation for a Small Standard Camera. *Photogrammetric Record.* 13(78): 909-9 16.

Wilhelm, H. G.

1993 *The Permanence and Care of Color Photographs: Traditional and Digital Color Prints, Color Negatives, Slides, and Motion Pictures.* Preservation Pub. Co. Grinnell, Iowa

Wolf, P. R.

1983 *Elements of Photogrammetry, with Air Photo Interpretation and Remote Sensing.* McGraw-Hill, Inc.