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

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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.

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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

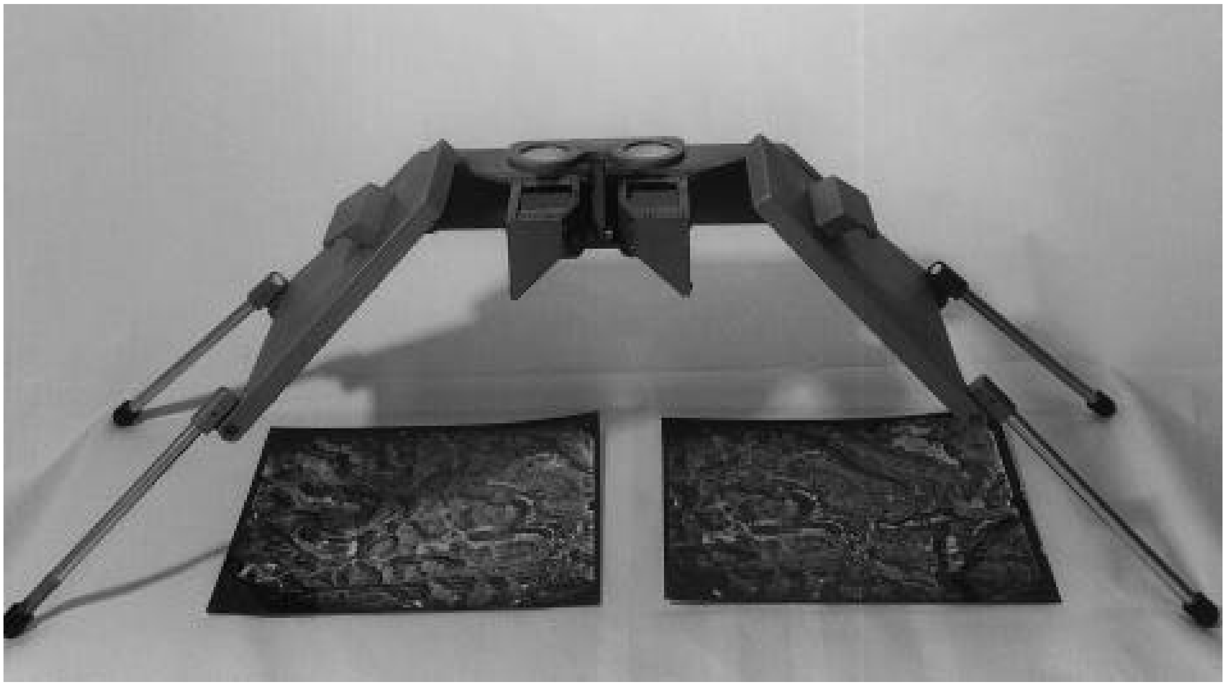

Figure 1. A mirror stereoscope

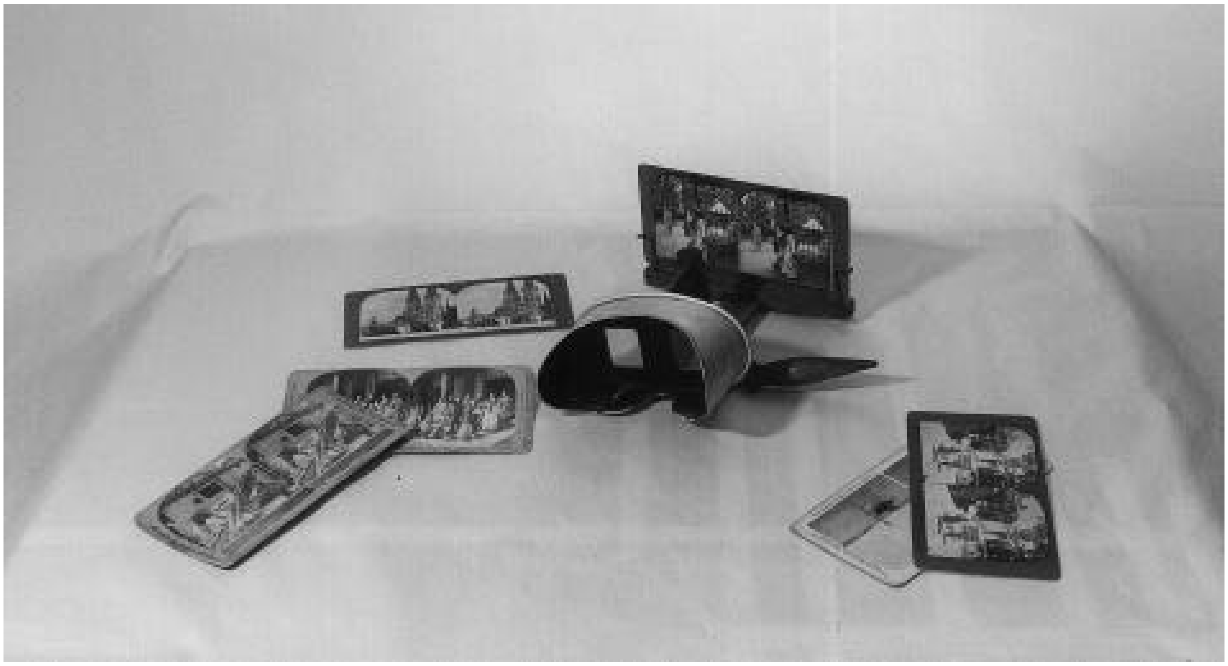

Figure 2. A parlor stereoscope

eye-training, one can perceive the three-dimensional effect by placing the 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.

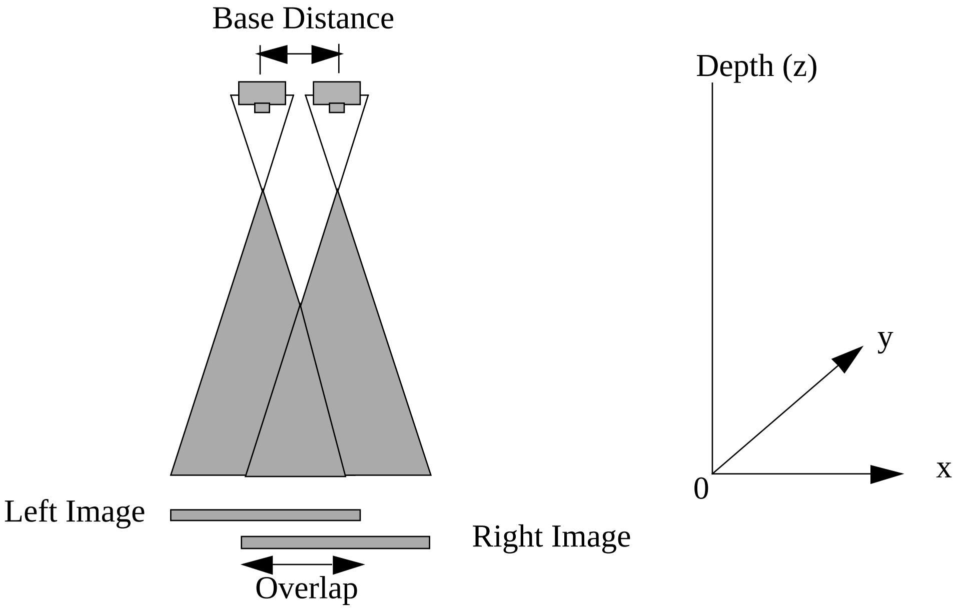

Figure 3. Photographs taken with a 60 percent overlap

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.

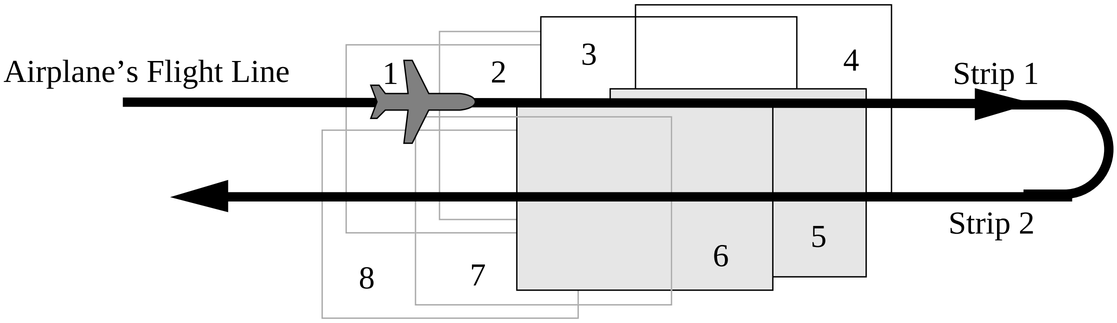

Figure 4. Generating aerial stereo images

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).

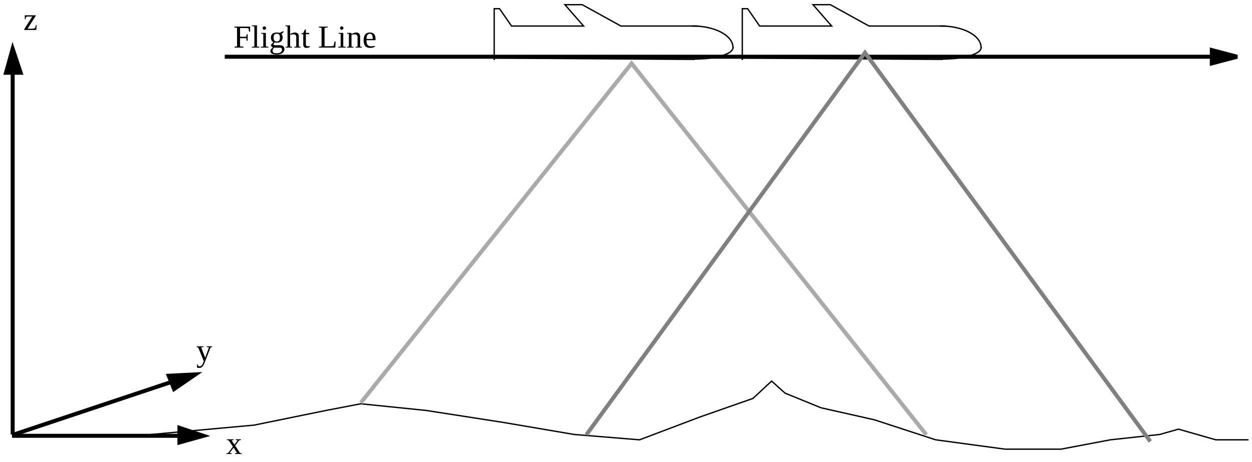

Figure 5. Taking aerial photographs along a flight line

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 IO, 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 IO 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).

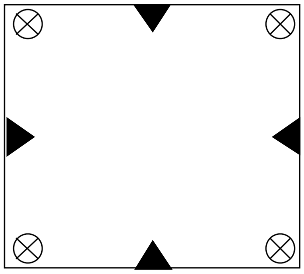

Figure 6. A typical example of fiducial marks

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.