# An Analytical System for Close-Range Photogrammetry

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ABSTRACT: An analytical photogrammetric system using non-metric cameras and data reduction software has been developed. Important factors influencing the development, such as camera calibration and project design, are described. The system has been experimentally tested and found to yield accurate results. These results suggest that this system is suitable for application in construction surveys, bioengineering, quality control, surface modeling, etc.

## INTRODUCTION

THE DEMAND for increasingly accurate surveying and mapping methods in areas such as construction, material testing, bioengineering, quality control, and surface modeling is commonly known among engineers. New and expanded applications of close-range photogrammetry are being developed to meet these needs. Close-range photogrammetry is attractive for various applications because it can simultaneously measure, with great accuracy, a large number of points without interfering with the subject being measured. The points being measured may be in a static or dynamic state and all $X$, $Y$, $Z$ coordinates are determined either in a local reference system (shape measurements) or in a global reference system (spatial measurements). Close-range photogrammetry has also the advantage of being economical, fast to perform, and able to create permanent records of the subject being measured in the form of photographs.

New and promising methods that can deliver accuracy are always of interest. Recently, there was an opportunity to develop and test an analytical system for close-range photogrammetry at California State University, Fresno. In developing the system, full and purposeful advantage was taken of the availability and low cost of advanced technology. This included non-metric cameras, microcomputers, and measuring microscopes. With these items an inexpensive close-range photogrammetric system was produced that provides reasonable accuracy.

The testing of the system is based on a series of construction surveys using a 35-mm camera (Hatzopoulos, 1985). The major factors influencing the development and performance of the system are camera calibration, photogrammetric project design, data aquisition, and data processing.

## CAMERA CALIBRATION

Non-metric cameras provide satisfactory image quality in terms of resolution, but there is a substantial geometric distortion that averages about 0.040 mm and reaches as high as 0.200 mm. The quality of the standard 35-mm camera lens, for example, is such that most of the distortion (about 90 percent) is radial, with a smaller amount of tangential distortion. The small format size of some cameras (35 mm by 26 mm) has the advantage of reducing film deformations, in terms of unflatness and shrinkage, to a minimum as compared to the larger format cameras. The greater advantages, however, are their ability to focus precisely within the range of most application projects and the capacity to create a desirable image scale by interchanging lenses. Other advantages, such as being handy and inexpensive, are a plus of using a small format non-metric camera. The calibration process is composed of the following steps: installation of the fiducial marks, field calibration, and testing.

*The installation of the fiducial marks* does not pose any particular difficulty, but the calibration of the fiducial marks requires some processing. Processing is necessary to compute the coordinates of the fiducial marks with reference to a coordinate system which has as its origin the intersection of the diagonals of the frame. The calibration of the fiducial marks is performed by measuring, in a monocomparator, several points along each edge of the frame, together with the fiducial marks, and using a software package to reduce all measurements to the intersection of the diagonals of the frame.

*The field calibration* for lens distortion, principal distance, and principal point determination requires a well-designed, three-dimensional test field with appropriate targeting. There are two such test fields for camera calibration at California State University, Fresno. One is designed for one-metre distance, finite-focus calibration and the other for calibration focusing at infinity. As shown in Brown (1971), camera calibration at infinity and at finite focus will provide enough information to calculate the distortion coefficients at any other focusing distance. The targets on each test field are precisely determined

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using a one-second theodolite and they are adjusted using a rigorous least-squares plane surveying package (Hatzopoulos, 1983). The accuracy of the one-metre control field was tested to be 0.015 mm and the accuracy of the control field at infinity was tested to be 0.040 mm. The idea of implementing a precisely measured control field for camera calibration is to directly relate the inner orientation parameters of the camera to the accurately determined coordinates of the object space. Such a process has also been reported by Abdel Aziz and Karara (1971) and by Karara and Abdel Aziz (1974).

*Testing* was performed by utilizing two different processing methods. One method is based on the finite element method (Munjy, 1983). This method uses a variable principal distance over the entire picture domain. The other method uses the traditional odd-powered polynomial with decentering coefficients of distortion (Abdel Aziz, 1973; Brown, 1971; Karara and Abdel Aziz, 1974). Both methods were found to provide about the same results. Radial lens distortion curves of the four diagonals of the Olympus OM-2N 35 mm camera are given in Figure 1. The calibration was performed by the finite element method and the distortion was interpolated from the equivalent variable principal distance functions.

## PROJECT DESIGN

Reports dealing with project design have been published by many authors (Brown, 1980; Chen *et al.*, 1983; Fraser, 1984; Hatzopoulos, 1979). The main components of the design are accuracy requirements, instrumentation, geometric configuration, redundancy, the definition of the datum, and the processing method.

*The accuracy requirements* vary depending on the type of the project. In building construction, for example, an accuracy of 5 mm is satisfactory (Abdel Aziz, 1979). The accuracy this system has been designed to achieve is to be better than 1 part per 5000 of the largest dimension of the object surveyed.

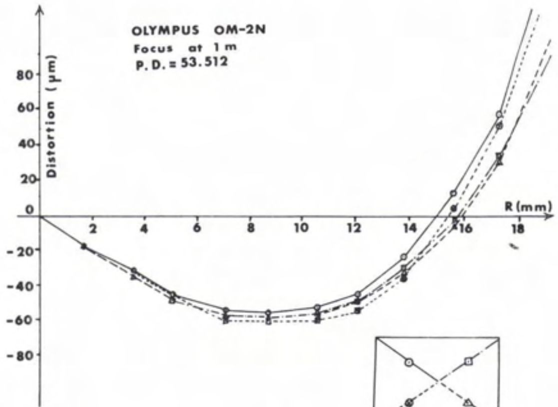


FIG. 1. Radial lens distortion of the standard 50-mm lens of the Olympus OM-2N 35-mm camera.

*The instrumentation* starts with the camera system, in the test case a 35-mm camera associated with a variety of lenses. The points on the negative can be measured on a comparator or other measuring device to a 0.001-mm precision. A toolmaker's microscope is an alternative to the comparator measuring device, but it has not yet been tested for this system. It is necessary to have very well-defined targets located at all object space points that are going to be measured. Black circles on white backgrounds provide well-defined images. Retrotargets have also been found to be excellent in close-range photogrammetric applications (Brown, 1980).

*The geometric configuration* may have some restrictions depending on various conditions, obstacles, etc., that may be overcome to a certain degree by the flexibility of the non-metric camera and its ability to provide a desirable image scale by mounting the proper lens. Favorable geometry may be facilitated by using an aerial platform (Hatzopoulos, 1979), but this may increase the cost. A geometric configuration with three camera stations (Figure 2), providing parallactic angles of 40 to 130 degrees and having a 100 percent overlap, would be enough to satisfy the accuracy requirements (Hatzopoulos, 1979).

*The redundancy* depends on the number of photographs and the degree of overlap among the photographs. A minimum of three photographs with 100 percent overlap is found to provide a reasonable level of redundancy.

*The datum* is not always necessary to be globally defined, particularly when the shape of the object is to be surveyed. Shape change may be a significant factor in quality control measurements, but in other applications, such as construction surveys, it is a particular case of structural monitoring. Building construction surveys, for example, require a reference datum composed of a horizontal plane and the plumb line. The coordinate system is established by defining the $X,Y,Z$, axes. The $X$ and $Z$ axes are laid on a horizontal plane and the $Y$ axis is parallel to the plumb line (Figure 2). A simple way to define the datum in the object space is by having three control points with known $X,Y,Z$, coordinates. The stability of the datum depends on the location of the control points. It has been found that the most favorable locations for the control points will constitute a triangle with maximum area (Hatzopoulos, 1979). The control points may be placed on the structure or they may be placed in other available locations. If the media carrying the control points is not stable, then the control points must be surveyed at the same time the photography is taken. The measurement of the control points can be performed by a theodolite occupying at least two baseline stations located on stable ground (Figure 2). If

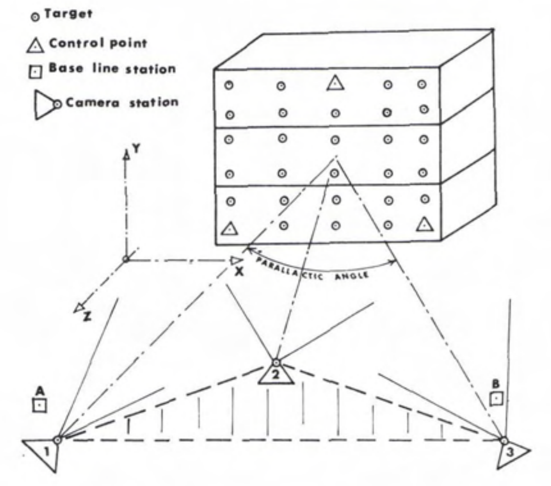


FIG. 2. A typical geometric configuration of a photogrammetric construction survey system.

the shape of the object is to be measured, then the three control points may be determined by precisely measuring the three distances between those points.

*The processing method* provided by this system is based on the least-squares bundle adjustment.

## SOFTWARE ANALYSIS FOR DATA PROCESSING

Data processing is carried out by an interactive close-range photogrammetry software package developed by the author, that is composed of a data base system with network structured files, and several program modules that are attached to the data base and perform the various operations (Figure 3). A similar integrated software configuration, but for aerial triangulation, together with geodetic observations, has been reported by Elassal (1983).

The processing program modules involve image coordinate transformation, i.e., conformal, affine, and bilinear; image coordinate refinement, such as radial and tangential lens distortion, principal point correction, or finite element with variable principal distance refinement (Munjy, 1983); resection to determine the exterior orientation elements of the camera stations; intersection to obtain preliminary coordinates for the object points; and least-squares bundle adjustment to obtain the final adjusted coordinates and their covariances. This system is capable of handling several sets of photographs with each set having, at the present, up to 15 photographs.

There are several other program modules that are attached to the data base, including camera calibration, calculation of differences of the same points in two different sets, conformal transformation of one set to another set, and calculation of the average photographic distance, etc. The organization of the photographs into sets enables the data base to handle data of the same project, but in different epochs, which is necessary in such a case as structural monitoring. This organization of the data base is also supporting static and dynamic tests on structure and construction material testing with different loading. The general organization of the software (Figure 3) permits data entry into the data base from various media by using input files, or interactively by the operator. All information in the data base can be unloaded at any moment into a batch file for archiving or back up purposes, or it may be loaded back into the data base from the batch file. The network structure of the data base files permits fast access of the information and it may contain some redundant information, but the storage that is occupied by the extra pieces of information and the extra sorting time performed by the data base software is insignificant as compared to the savings in time and storage during the operations of the processing program modules.

## EXPERIMENTAL TESTING

The testing area was selected to be the back wall of the first level of the East Engineering Building at California State University, Fresno. This wall is made of concrete and there are two concrete columns in the front, thus forming enough depth for establishing a three-dimensional test field (Figure 4). The targets were designed to provide movement in a direction perpendicular to the wall surface. This direction coincides with the Z direction of the photogrammetric survey system. The target is composed of a sphere having diameter of ¾ inch, and the sphere can be moved between two nuts mounted on fixed positions along a screw that is rigidly attached to the wall. The target can thus be placed into two distinct positions; position one where the target is close to the wall and position two where the target is away from the wall. The distance between the two target positions was measured precisely to 0.1 mm by a vernier scale. A total of 21 targets were mounted on the wall for the experimental testing. The camera station configuration is shown in Figure 4. A total of two sets, with

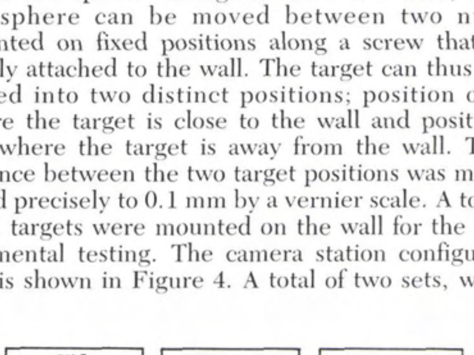


FIG. 3. Software organization for data processing.

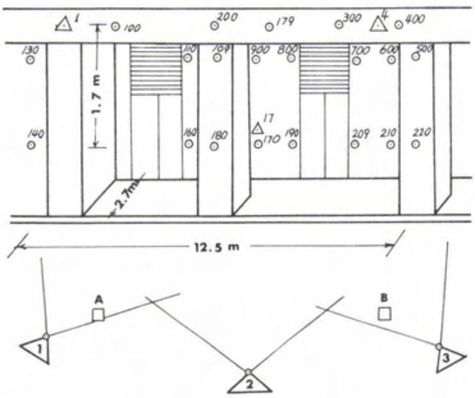


FIG. 4. The test site for the practical evaluation.

three photographs in each set, were finally obtained using an Olympus OM-2N 35-mm camera with a standard 50-mm lens. The first set was obtained with all targets being in position one. The second set was obtained with all targets being in position two. The average photographic distance was calculated to be 18.777 metres. There were three control points (as shown in Figure 4) to define the datum and to aid the space resection operations. The image coordinates of all target points, together with the fiducial marks, were measured on a Kern MK-2 monocomparator. The measured image coordinates, together with the camera calibration data and the control point coordinates, were processed using the software package described previously. Three of the measured points were dropped as having significantly large errors, and the remaining 18 points were used to evaluate the system's performance.

A part of the processing results of this experiment is given in Table 1 and it is illustrated in Figure 5. Table 1 is composed of 12 columns as follows: column one, labeled as PNM, contains the point number, and columns 2, 3, 4, and 6, 7, 8 contain the standard errors of object space coordinates of each set as they were calculated from the covariance matrix of the bundle adjustment. Columns 5 and 9, labeled CST, indicate the camera station numbers participating in the bundle adjustment for the corresponding point (camera stations are numbered as 1, 2, 3; see Figure 4). Column 10, labeled as D′, contains the calculated difference of the Z coordinate using the two sets of data ($Z2 - Z1$). Column 11, labeled as D, contains the precisely measured distance the target was moved. Finally, column 12 contains the error ($D' - D$). Figure 5 illustrates the planimetric location of the targets projected in the $XY$ plane. The error ellipses express the position accuracy in the $XY$ plane and the arrow vectors illustrate the error shown in Table 1, column 12.

The RMS error of the selected 18 points is 1.9 mm which is about one part per 7,000 of the largest distance in the object space. The RMS error of all Z coordinates in set one, as shown in Table 1, column 4, is 1.7 mm and the RMS error of all Z coordinates in set two, as shown in Table 1, column 8, is 1.8 mm. These results indicate that there is no significant difference in the error of the Z direction as expressed either by the covariance matrix of the system or determined by comparing photogrammetrically calculated values to direct measurements.

## CONCLUSIONS

The results in the experimental evaluation indicate that the developed system, operating with a

TABLE 1. FINAL RESULTS OF EXPERIMENTAL TESTING
(ALL DIMENSIONS ARE IN MM)

| PNM | SX1 | SY1 | SZ1 | CST | SX2 | SY2 | SZ2 | CST | $D'$ | $D$ | $D$-$D'$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 | 1.03 | 0.83 | 1.26 | 321 | 1.05 | 0.83 | 1.26 | 321 | 29.4 | 28.8 | −0.6 |
| 109 | 0.97 | 0.72 | 1.18 | 321 | 0.99 | 0.73 | 1.18 | 321 | 25.9 | 25.7 | −0.2 |
| 110 | 1.24 | 1.14 | 2.36 | 21 | 1.25 | 1.14 | 2.35 | 21 | 27.4 | 27.5 | 0.1 |
| 130 | 1.20 | 1.01 | 1.51 | 321 | 1.21 | 1.01 | 1.49 | 321 | 33.4 | 29.1 | −4.3 |
| 140 | 1.22 | 1.04 | 1.53 | 321 | 1.23 | 1.05 | 1.51 | 321 | 29.5 | 28.4 | −1.1 |
| 170 | 1.08 | 0.94 | 1.55 | 321 | 1.09 | 0.94 | 1.55 | 321 | 24.3 | 26.4 | 2.1 |
| 179 | 0.98 | 0.73 | 1.20 | 321 | 1.00 | 0.74 | 1.21 | 321 | 32.6 | 29.4 | −3.2 |
| 180 | 1.00 | 0.78 | 1.22 | 321 | 1.02 | 0.79 | 1.22 | 321 | 33.5 | 33.1 | −0.4 |
| 190 | 1.85 | 1.05 | 2.79 | 32 | 2.07 | 1.06 | 3.03 | 32 | 18.4 | 19.6 | 1.2 |
| 200 | 1.00 | 0.76 | 1.21 | 321 | 1.02 | 0.76 | 1.21 | 321 | 28.4 | 26.4 | −2.0 |
| 209 | 1.37 | 1.20 | 2.62 | 21 | 1.40 | 1.21 | 2.62 | 21 | 27.6 | 27.1 | −0.5 |
| 210 | 1.33 | 1.12 | 2.18 | 321 | 1.47 | 1.19 | 2.23 | 31 | 25.2 | 28.4 | 3.2 |
| 220 | 1.07 | 1.02 | 1.60 | 321 | 1.09 | 1.02 | 1.61 | 321 | 30.5 | 32.4 | 1.9 |
| 300 | 0.97 | 0.77 | 1.26 | 321 | 0.99 | 0.77 | 1.27 | 321 | 22.1 | 20.5 | −1.6 |
| 400 | 1.01 | 0.86 | 1.40 | 321 | 1.03 | 0.87 | 1.41 | 321 | 30.1 | 28.4 | −1.7 |
| 500 | 1.07 | 0.92 | 1.55 | 321 | 1.10 | 0.92 | 1.57 | 321 | 22.2 | 24.8 | 2.6 |
| 600 | 1.36 | 1.11 | 2.14 | 321 | 1.49 | 1.19 | 2.18 | 31 | 23.6 | 23.5 | −0.1 |
| 900 | 1.09 | 0.95 | 1.50 | 321 | 1.10 | 0.95 | 1.50 | 321 | 28.1 | 27.1 | −1.0 |
| R.M.S. Error | | | 1.7 | | | | 1.8 | | | | 1.9 |

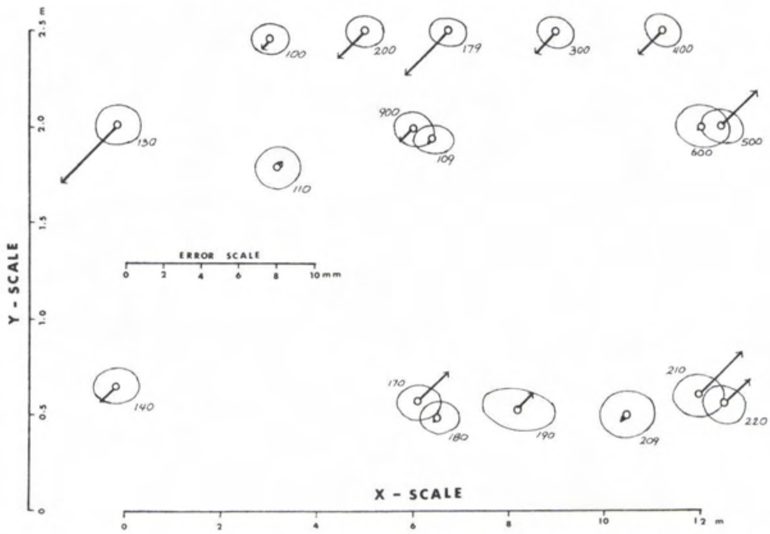


FIG. 5. A planimetric view of the measured points projected in the *XY* plane. The position accuracy in the *XY* plane is expressed by the error ellipse. The measured error in the *Z* direction is expressed by arrow vectors.

35-mm non-metric camera (Olympus OM-2N), provided an accuracy of 1 part per 7000 of the largest dimension of the object space. The accuracy can also be increased by increasing the number of photographs. It is very important to maintain a parallactic angle between 40 to 130 degrees and also a certain amount of redundancy (at least three 100 percent overlaping photographs) to obtain results of sufficient accuracy and reliability.

The accuracy obtained by the developed system would be a fraction of a millimetre for objects having their largest dimension smaller than 7.0 metres, thus making the system suitable for a great variety of applications, such as engineering, bioengineering, medicine, quality control, police crime investigation, etc. Potential construction survey applications include monitoring deformations in critical areas (Brown, 1980; Chen *et al.*, 1983; Hatzopoulos, 1979; Veress *et al.*, 1980), building construction (Abdel Aziz, 1979; Granshaw, 1980), piping layout operations, ship construction (Kenefick, 1977), and public utilities (Danko, 1979). Potential bioengineering applications are as follows: mapping the human body for orthopaedic artificial limb construction (Kratky, 1975), plastic surgery (Atkinson, 1974), monitoring changes in the human body such as athlete development and physical therapy (Bugyi, 1974), and measuring organs for transplant operations (Karara and Marzan, 1973).

Non-metric cameras provide enough resolution to obtain the proper image quality. They are flexible enough to provide a desirable image scale from a particular camera station by interchanging lenses or by using a zoom lens. The systematic error of the geometric lens distortion can be easily modeled by either using the odd-powered polynomial method or by using the finite element method, and it can be precisely determined through a field calibration process. The film has a minimum amount of deformation because of the small format of the frame. Non-metric cameras are inexpensive and, being readily portable, very easy to operate.

A very important element of the developed system is the processing software and, particularly, the data structure and organization. The software used in this project was found to be a very efficient package, with interactive menus to control the operations, thus reducing the processing time to a minimum. The data structure permits easy modification and expansion of program modules. Expansion is planned in the near future for project design through simulated observations.

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## REFERENCES

Abdel Aziz, Y. I., 1973. Lens Distortion and Close Range, *Photogrammetric Engineering*, Vol. 39, pp. 611-616.

———, 1979. An Application of Photogrammetric Techniques to Building Construction, *Photogrammetric Engineering and Remote Sensing*, Vol. 45, No. 4, pp. 539-544.

Abdel Aziz, Y. I., and H. M. Karara, 1971. Direct Linear Transformation from Comparator Coordinates into Object Space Coordinates in Close-Range Photogrammetry, *Proceedings of the Symposium on Close-Range Photogrammetry*, University of Illinois, Urbana.

Atkinson K. B., I. Newton, and B. D. G. Morgan, 1974. A Note on Volume Determination in Connection with Reconstruction Surgery, *Biostereometrics 74*, Washington D.C.

Bugyi, B., 1974. Photogrammetric Determination of the Body Composition of the athletes, *Biostereometrics 74*, Washington D.C.

Brown, D. C., 1971. "Analytical Calibration of Close-Range Cameras," Paper presented at the 1971 Symposium of Close-Range Photogrammetry, University of Illinois, Urbana.

———, 1980. *Applications of Close-Range Photogrammetry to Measurements in Orbit*, Volume 1 of a Final Report submitted to the Rockwell International Space Systems Group Dept. 379. Contract No. MOM7NDS-895942.

Chen, Y. Q., M. Kavouras, J. M. Secord, 1983. Design Considerations in Deformation Monitoring, *Proceedings of the 17th FIG Congress*, Sofia Bulgaria, Paper 608.2.

Danko, J., 1979. Application of Close-Range Photogrammetry in Public Utilities and Piping Models, *Photogrammetric Engineering and Remote Sensing*, The Close-Range Column, November 1979.

Elassal, A. A., 1983. Managing Mapping Data Using Commercial Data Base Management Software, *Proceedings of the 17th FIG Congress*, Sofia Bulgaria, Paper 514.4.

Fraser, C. S., 1982. Optimization of Precision in Close-Range Photogrammetry, *Photogrammetric Engineering and Remote Sensing*, Vol. 48, No. 4, pp. 561-570.

———, 1984. Network Design Considerations for Non-Topographic Photogrammetry, *Photogrammetric Engineering and Remote Sensing*, Vol. 50, No. 8, pp. 1115-1126.

Granshaw, S. I., 1980. Bundle Adjustment Methods in Engineering Photogrammetry, *The Photogrammetric Record*, Vol. 10, No. 56.

Hatzopoulos, J. N., 1979. *Combination of Aerial and Terrestrial Photogrammetry in Structural Monitoring*, Dissertation, University of Washington.

———, 1983. PLSUR5 A Computer Program for Simultaneous Plane Network Adjustment by a Desk Top Computer, *Proceedings of the ACSM-ASP Fall Convention*, Salt Lake City.

———, 1985. Photogrammetric Construction Surveys by a 35 mm Camera, *Proceedings of the ASP 51st Annual meeting*, Washington, D.C.

Karara, H. M., and Y. I. Abdel Aziz, 1974. Accuracy Aspects of Non Metric Imageries, *Photogrammetric Engineering*, Vol. 37, pp. 1007-1117.

Karara, H. M., and G. T. Merzan, 1973. Determination of the Geometry of Tri-Leaflet Aortic Heart Valves, *Proceedings, SPIE Seminar-in-Depth on Quantitative Imagery in the Biomedical Sciences-II*, San Diego.

Kenefick, J. F., 1977. Applications of Photogrammetry in Shipbuilding, *Photogrammetric Engineering and Remote Sensing*, Vol. 43, No. 9, pp. 1169-1175.

Kratky, V., 1975. Photogrammetric Digital Modeling of Limbs in Orthopaedics, *Photogrammetric Engineering and Remote Sensing*, Vol. 41, No. 6, pp. 741-752.

Munjy, R. H., 1983. Camera Calibration Using the Finite Element Approach, *Proceedings of the ASP 49th Annual Meeting*, Washington D.C.

Veress, S. A., N. C. Jackson, and J. N. Hatzopoulos, 1980. Monitoring a Gabion Wall by Inclinometer and Photogrammetry, *Photogrammetric Engineering and Remote Sensing*, Vol. 46, No. 6, pp. 771-778.

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