Application of photogrammetric technique to astronomical telescope measurement and control

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ABSTRACT

The photogrammetry technique is widely used for measuring 3-D shape in diverse industries thanks to its easy implementation and straightforward algorithm. However, most measurements done by this technique are using a single camera with multi-exposure and the results are derived after a period of time. Along with the development of the CCD and computer technology, it is now possible to use multi-camera, real-time photogrammetric measurements and the results could be derived without much time delay. A multi-camera system avoids the error caused by time-delayed exposure. So the new technique could be widely used in telescope surface or position measurement and control. In this paper, the pertinent formulations, implementation and application details are discussed before a general conclusion is drawn.

Keywords: Photogrammetry, multi-camera, real-time, astronomy, telescope, measurement and control

1. INTRODUCTION

Photogrammetry is the science of dimension measurement that allows for full-field coordinate measurements to be taken from multiple photographs or images of physical objects to be measured. In the past, photogrammetry was mostly used in topographic surveying, as known as topographic photogrammetry, where the heights of land, trees, and buildings could be taken by flying over and taking multiple overlapping photographs.[8, 9] The information was drawn directly from the measurement of the photographs. The images used were on papers, films or negatives. These image coordinate measurements may be linear or angular, and may be between pairs of image points, or between image points and some reference marks. Some mathematical operation and algorithm were used to make the equations that combined these images into a three-dimensional picture possible to process with the tools at hand. From these image measurements, real 3-D coordinates and position of the measured objects in the photographs could be re-established. This technique had been used almost since the invention of photography. However, the data gathering and the result reduction usually took days or weeks of work. In recent years, thanks to the development of technologies and devices of digital image processing and computer vision, photogremmetry technique has undergone rapid development. Along with the development of CCD cameras and digital computers, the measurements of photographs could be easily implemented directly from inside the camera and the coordinate results could be found not in days but in hours or minutes. Therefore the technique has been widely used in many more fields, including astronomical telescopes. Now photogremmetry together with theodolite measurement, laser ranger technique and radio holography are very important tools in surface shape measurement. Photogrammetry has been used in such diverse fields as auto industry, aerospace industry, archaeology, architecture, bioengineering, civil engineering, forensic analysis, mechanical inspection, plant engineering, and surgery, as well as in the field of astronomical radio telescope, antenna. Moreover, automatic online or real-time inspection and recognition issue can be converted to the 3-D measurement of an object under inspection, so it is possible to apply photogrammetry technique to online measurement and hence real-time active control of telescope structure and antenna panel.[7] However, there is no exact real-time photogrammetry existing yet. In this paper, we propose a direct, multi-camera, real-time photogrammetry for future telescope surface or position measurement and control. In the same time, detailed formulae for coordinate calculation and data fitting are provided and implementation details are discussed. Application considerations and typical instances are also elaborated.

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2. PHOTOGRAMMETRY BASICS

Photogrammetry is essentially a 3-dimensional coordinate measuring technique that manipulates images to retrieve information for measurement and further for monitoring and controlling application. Similar to human eyes, photogrammetry uses at least two photographs or images of the object from different viewpoints to develop/percept depths of points on the object's surface. The inherent fundamental principle is triangulization, which is also employed by theodolites for measuring 3D coordinates, however, unlike theodolites, photogrammetry can get multiple points at a time with virtually no limit on the number of simultaneously triangulated points.

Actually, the photogrammetric technique involves two stages of operation, i.e., photography and metrology, which are both technically important for implementation of photogrammetry. Photography deals with taking images of measured objects, in which the photographic projection principles are involved. Specifically, Photography converts the real 3-dimensional objects into flat 2-dimensional images, and is a transformation or mapping process realized by camera on the CCD surface. Since the dimensions are decreased by photographic process, some original information is inevitably lost so that we cannot completely record the 3-dimensional object onto its 2-dimensional image.

Metrology is the following process that is just converse to the first stage, photography. It converts or maps the flat 2-dimensional images back into the real 3-dimensional world. However, since information is lost in the photographic process, we cannot reconstruct the 3-dimensional objects completely with just one photograph. As a minimum, we require two different photographs to reconstruct the 3-dimensional world. If this process was perfect, the two photographs are more than enough information to perfectly rebuild the 3-dimensional objects they represent. And in general, more photographs are taken to use extra information in them to improve the process to finally retrieve the 3-dimensional coordinates.

3. MATHEMATICS OF BACKPROJECTION

Mathematically speaking, photogrammetry is a back projection problem. Objects or targets in 3-D coordinates are projected into the CCD surface through a camera lens. From Methley(1986), the relationship between the object coordinates and the CCD image plane coordinates is:

$$x = -d\,\frac{(X - X_c)m_{11} + (Y - Y_c)m_{12} + (Z - Z_c)m_{13}}{(X - X_c)m_{31} + (Y - Y_c)m_{32} + (Z - Z_c)m_{33}}$$
$$y = -d\,\frac{(X - X_c)m_{21} + (Y - Y_c)m_{22} + (Z - Z_c)m_{23}}{(X - X_c)m_{31} + (Y - Y_c)m_{32} + (Z - Z_c)m_{33}} \qquad (1)$$

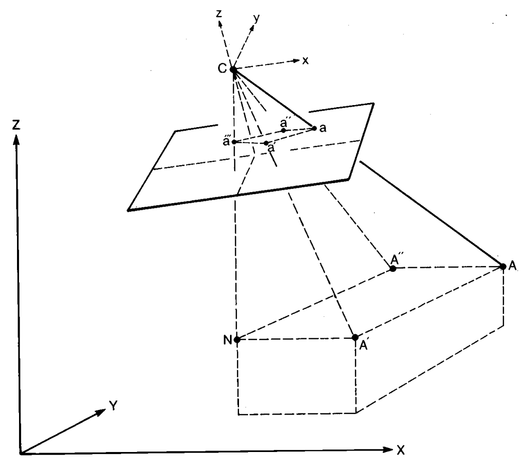

Fig. 1. Object and camera coordinate in photogrammetry

In the equations, d is the camera focal length, and R is the rotation matrix of the camera coordinates relative to the globe coordinate system, so:

$$M = R^{-1} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}^{-1} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \tag{2}$$

Equation (1) could be re-written for the object coordinates as:

$$\begin{aligned} (X - X_C) &= (Z - Z_C)\frac{(r_{11}x + r_{12}y + r_{13}(-d))}{(r_{31}x + r_{32}y + r_{33}(-d))} \\ (Y - Y_C) &= (Z - Z_C)\frac{(r_{21}x + r_{22}y + r_{23}(-d))}{(r_{31}x + r_{32}y + r_{33}(-d))} \end{aligned} \tag{3}$$

The above equations are for one single object point. In these two equations, there are altogether 12 variables involved. These are respectively 3 object point coordinates, 2 CCD image point coordinates, 1 camera focal length, 3 camera linear coordinate positions and 3 camera angular coordinate positions. The problem of modern day photogrammetry is usually to derive the 3-D object point coordinates from their 2-D image point coordinates. So the real variables of the system are 9 instead 12 as the focal length of camera is usually known beforehand and the camera image coordinates are known through CCD read out process. The number of variables could be further reduced by taking the global coordinate system same as the object coordinate origin. Without the knowledge of the object coordinates, one picture is not enough to solve the system equations as there are three variables for each data point. Therefore in real situation, the problem is solved by using more cameras or more camera positions in the system. By adding one more camera, there will be 6 more variables and two more equations for each object point. For solving the two camera system, if we choose the coordinates of the first camera as the object coordinate, we require at least 6 object points on both CCD camera planes. In this way, the variable number and the equation number are equal. However, these equations are not really independent. They will have an infinite number of solutions. Therefore, it is necessary to introduce a scale dimension either for camera distance or a scale dimension in the object space. With this condition, the photogrammetry problem could be solved by iteration and linearization. If multiple cameras are used in the system, the object position can be estimated even more accurately as there are redundant equations provided. The variable number for a multi-camera system is 6(m-1)+3n, where m is the camera number and n is the object point number. However, the number of equations derived from photogrammetry is 4n. With more target points used, the number of equations is much larger than the variable number in the system. With modern day computers, the photogrammetry equations could be easily solved in almost real-time.

4. GENERAL DATA FITTING

The measured target point coordinates are a set of numbers in 3-D space. These numbers have to be compared with a given set of coordinates to determine the surface errors. The given set of coordinates could be some predetermined shape or derived from the system design. If the given data is available, this becomes a general data fitting problem. If there are two sets of data points $X=\{\mathbf{x}_1,\mathbf{x}_2,\ldots,\mathbf{x}_n\}$ and $Y=\{\mathbf{y}_1,\mathbf{y}_2,\ldots,\mathbf{y}_n\}$, after a best fitting process, the variance between these two sets of data points is defined as (Umeyama,1991):

$$\varepsilon^2(R,\mathbf{t},c) = \frac{1}{n}\sum_{i=1}^{n}\left\|\mathbf{y}_i - (cR\mathbf{x}_i + \mathbf{t})\right\|^2 \tag{4}$$

where R（rotation）， $\mathbf{t}$（displacement） and c（scale）are necessary transformation matrices for the system of the two sets of data points. It is possible to pre-set one or all of the matrices. Then the variance of the two data points after the transformation is:

$$\varepsilon^2(R,\mathbf{t},c)=\sigma_y^2-\frac{[tr(DS)]^2}{\sigma_x^2} \tag{5}$$

Where, *tr* is the trace of a matrix, that is

$tr(A)=\sum_{i=1}^{n} a_{ii}$, also

$\sigma_x^2=\frac{1}{n}\sum_{n=1}^{n}\|\mathbf{x}_i-\boldsymbol{\mu}_x\|^2$, $\sigma_y^2=\frac{1}{n}\sum_{n=1}^{n}\|\mathbf{y}_i-\boldsymbol{\mu}_y\|^2$, $\boldsymbol{\mu}_x=\frac{1}{n}\sum_{n=1}^{n}\mathbf{x}_i$, $\boldsymbol{\mu}_y=\frac{1}{n}\sum_{n=1}^{n}\mathbf{y}_i$,

$\Sigma_{xy}=\frac{1}{n}\sum_{n=1}^{n}(\mathbf{y}_i-\boldsymbol{\mu}_y)(\mathbf{x}_i-\boldsymbol{\mu}_x)^T$.

Matrix $\sum_{xy}$ has a singular value decomposition as UDV^T, where $D=diag(d_i)$ and $d_1 \geq d_2 \geq \ldots \geq d_m \geq 0$. S is:

$$S=\begin{cases} I & det\,\Sigma_{xy}\geq 0 \\ diag(1,1,\cdots,1,-1) & det\,\Sigma_{xy}<0 \end{cases} \tag{6}$$

If the rank of $\sum_{xy}$ is larger or equal to m-1, then the transformation matrices are:

$$\begin{aligned} R&=USV^T \\ \mathbf{t}&=\mu_y-cR\mu_x \\ c&=\frac{1}{\sigma_x^2}tr(DS) \end{aligned} \tag{7}$$

In the above equations, if the rank of $\sum_{xy}$ is m-1, then:

$$S=\begin{cases} I & det\,U\,det\,V=1 \\ diag(1,1,\cdots,1,-1) & det\,U\,det\,V=-1 \end{cases} \tag{8}$$

5. PHOTOGRAMETRY IMPLEMENTATION CONSIDERATION

For realistic implementation, some considerations are necessary for both processes of photogrammetry. Three main considerations are significant for good photography. These are field of view, focusing and exposure. As for metrology performance, triangulization, calibration and distance scale are of effective importance.[9]

5.1. Field of view

The camera's field of view defines how much it sees. The wider the field of view, the more the camera sees from a given location. In general, there is a tradeoff between the field of view of a lens and the accuracy of the camera system. Although wider-angle lenses need less room around the object, they also tend to be less accurate. To select a camera with an appropriate field of view is quite primary for the employment of photogrammetry.

5.2. Focusing

Focusing the lens is to make the image sharp. The range of acceptable sharpness is called the depth of focus. Normally, for modern camera, focusing is automatically finished. For a CCD camera, it is necessary to mount with appropriate focusing.

5.3. Exposure

For photogrammetry purposes, it is desirable to set the targets bright and the background dim. When retro-reflective targeting is used, the target and background exposures are almost completely independent of each other. The target exposure is completely determined by the flash power while the background exposure is determined by the ambient illumination. The amount of background exposure is controlled by the shutter time.

5.4. Triangulization

Triangulization involves two aspects: Target position triangulization and Triangulization geometry. The former just means to require the target separations to be known accurately, and there is enough signal-to-noise in the CCD image so that interpolation of the centroid of the imaged targets can be performed to sufficient accuracy. Triangulization geometry means to figure out the relative positions between cameras and those between cameras and targets that form a number of triangles for mathematic reduction. Normally, it is necessary to number all the targets and all the cameras.

5.5. Calibration

Before carrying out measurement, cameras, CCD or lenses must be precisely calibrated to remove errors that are present in the system. The cameras should be calibrated at the time of measurement, and under the environmental conditions that exist (temperature, humidity, etc.) at the time of measurement. This is far superior to relying on an old and possibly outdated laboratory calibration that may have been done under dramatically different conditions than that existed at the time of measurement. And for a better thorough calibration you must measure a minimum number of images taken from a minimum number of different locations. Also, you must have a minimum number of well-distributed targeted points on each image and for the entire measurement.

5.6. Distance Scale

Photogrammetric measurements are inherently dimensionless. To scale a photogrammetric measurement, there must be at least one known distance, as means that, from the actual coordinates beforehand of some targeted points, it is feasible to compute the distances between these points and use these to scale the measurement. It is highly recommended to use more than one distance to scale the measurement, to enhance the scale accuracy, and more importantly, to help find scale errors.

5.7. Non-contact targeting

Normally, photogrammetry requires to target and/or touch points of interest on the object to be measured, which has been limited its acceptance in some areas. In recent years, there emerges a new non-contact targeting photogrammety technique that removes this constriction in particular applications. [13] The new technique is especially suited to surface measurement and non-contact metrology, for example, measurement of delicate precision antenna panel surface. Its main task is to remove the necessity to target the measured object. This paper examines a new non-contact targeting technique that uses a high power stroboscopic projector, which is commercially available, to project dots or "targets" onto the object. The target projection system is particularly well suited to surface measurement and non-contact metrology in general. The projector works much like an ordinary slide projector. A light source illuminates a target slide. This illuminated pattern passes through a series of lenses that magnify the slide and project and focused it onto the object. The actual construction of the projector is complicated by the need to accurately control the whole process. The greatest concern is the stability of the dot pattern, tantamount to moving the physical target point, during the measurement.

6. APPLICATION TO ASTRONOMICAL TELESCOPES

6.1. General consideration of application

Up to date, almost all photogrammetry uses a single camera, and multiple camera positions during the surface or target measurements. There is no widely used photogrammetry which is performed in the real time by multi-camera measurements. There are a number of reasons behind that. Firstly, it is rather difficult to form a global coordinate system by exposures on different camera positions. In any system or surface measured, there will be hundreds or thousands of target points. During the photogrammetry process, the targets form their images in the CCD cameras while the camera position and orientation are changed. It is very difficult for a computer or camera itself to establish the right global coordinate system and to get the right numbering of all these image points. In the practical photogrammetry, encoded target points have to be used for the computer or human to find the same image points of different exposures for the same object target point. Secondly, in the photogrammetry process, it is necessary to add scaled targets (targets with known distance between them) or other reference targets with known coordinate relationship. The scaled targets are used to finally solve the equations, and the other reference targets are used to get the estimation of the camera positions for further camera position iteration. It is also difficult for the computer to distinguish these special targets from other object targets. Human intervention is sometime necessary for dealing with these special targets. Thirdly, the cost of an accurate, large scale CCD camera and the related software used to be very expensive. This also makes the real-time multi-camera system difficult. Now the photogrammetry cameras used are mostly from photogrammetry professionals, the cameras will be used for various surface measurements under different working conditions. Fourth, the data memory cards for CCD pictures used to be limited and the computer calculation time which includes the data fitting and some fancy graphics was rather long, so the real-time process was impractical.

However, all these limitations have been changed along with the development of the CCD camera and the computer calculation technique. Now CCD cameras are very cheap and computer calculation is very fast. The software required is also not so difficult to write. It is now very promising to use a multi-camera, real-time photogrammetry system in the astronomical telescope field. This multi-camera, real-time photogrammetry could be used for surface or position setting. It could also be used to monitor or control any thermal or gravitational distortion of a structure, to find out the real surface shape of a structure or surface during the observation.

For astronomical antennas with a radome, the CCD cameras used for a real-time photogrammetry system could be arranged on the top of radome. Target points could be formed by projecting some laser light source to the surface through a small projector. Since the cameras are fixed over the dome, the global coordinate system correction could be performed more easily. There is no confusion for the computer to find out which image point is from which object target. The scaled target could be arranged in the fixed position of the antenna, so the software could find these image points easily. In this system, it may not be necessary to use encoded targets at all. These special targets require a special strategy in the software to be identified. Since all the cameras get the pictures in the same time, the photogremmetry could be done even during the antenna observing period. There will be no error caused by structure movement or other quick changes during photogremmetry process. For an Arecibo styled very large antenna, CCD cameras could be arranged on the suspended cables. High reflecting target tapes could be used as target points on the surface. If reflecting targets are used, it is necessary to used a flash light during exposure. If the photogrammetry process is connected to the control system, the information from the real-time calculation could be feed back to the control system to adjust the surface shape in the real-time. For a large optical mirror support system, multi CCD cameras have to be under the mirror supporting structures, and special photo diodes fixed on the support structures may be used as target points. Photogremmetry can be used for pre-setting the support system and for monitoring the system. At present, the accuracy of photogrammetry is about one part in 100,000 or even one part in 1,000,000, which is quite capable and sufficient for many applications.

6.2. Application to astronomical telescopes

Last century saw a variety of radio telescopes built, from the largest fixed Arecibo 305 m reflector to 100 m fully steerable dishes of Effelsberg and Green Bank, from single filled dishes to big interferometry arrays. In recent years, due to new science driver, the radio astronomy focus has been moving to wavebands such as that from the far infrared to sub-millimeter and to millimeter sections of the electromagnetic spectrum.[6] Because of operating frequency higher and corresponding wavelengths shorter than ever, the design of such telescopes is difficult. It involves a number of new technologies to achieve all weather stable surface and pointing accuracy of radio astronomical telescope, such as real-time precise measurement and control of antenna panels, further active surface technology is employed. Moreover, as the very highlights of current astronomical telescope advance, extremely large ground-based optical telescopes (ELT) are proposed and initiated, active and adaptive structure technique is promising to contribute to the realization of ELT projects.[14]

Seeing that delicate nature of some antenna panels and distant nature of antenna surface require non-contacting, optical structural measurement techniques. Photogrammetry is a leading candidate technology for measuring the static shape and/or motion of future telescope structures. It offers the simplicity of taking photographs with good to excellent measurement precision. Current digital photogrammetry can obtain 3-dimensional coordinate accuracies in the 25 μm range. Photogrammetry also allows multiple measurements to be taken simultaneously over a broad field of view. This makes the measurement technique appropriate for displacement measurements because of a static applied load, say, physical force or thermal effect, or positional repeatability. With related computer technologies advancement, it is possible to realize real-time measurement and control of radio telescope surface panels and structures by photogrammetry technique. Many existing radio telescopes used this technique to reset reflecting panels, such as Arecibo 305 m reflector, and newly developed sub-millimeter (SM) and millimeter antennas (MM) are using it to measure panels and to control surface. Its pholosophy is also used for active control of compensation for structural deformation of future ELT.

The Atacama Large Millimeter Array（ALMA）is an array of 64 Antennas with 12 m aperture making a total area up to 7,200 m^2. Thire Reflector Surface Accuracy goal is as high as some 20 microns. For the prototype antenna the contractor will provide a surface setting accuracy of 100 microns. Precision measurement of the surface was done by the ALMA Project using holography or may be done by using photogrammetry. [10]

The largest single fixed radio telescope in the world Arecibo 305 m reflector went into operation in 1963. Its spherical surface is composed of 38,788 perforated aluminium panels. Deviation of these panels from an ideal spherical surface requires routine reseting. Previous adjustment of this surface has been based upon theodolite measurements. For optimum performance requirment, the overall rms surface error should be less than 1/20 wavelength, namely 3 mm rms at 10 GHz, and it is believed that the panels themselves have an error of approximately 1 mm. Thus, the primary reflector surface adjustment error should ideally be below 2 mm rms, which could not be achieved by theodolite, Photogrammetry was chosen to be the only practical means to achieve this level of accuracy and photogrammetric surveys of the primary reflector surface were performed three iterations during 2000 to 2001.[11,12]

Thermal distortion is critical to space antennas and SM/MM antennas.[6, 15] There are many characteristics of photogrammetric measurements that enable it suitable for thermal-distortion measurements. One of the main benefits is that the system only needs an optical path between camera and to-be-measured object but not a physical one. This allows the measuring camera to be safely outside the thermal chamber or in a thermally conditioned environment while the to-be-measured object is exposed to extreme conditions. Another benefit is that in-plane distortion measurements are possible for photogrammetric measurement technique. Often, the objects are relatively flat and do not have features that can be used as landmarks, say, reflector dish for antennas. [13] Because photogrammetry uses small lightweight targets as landmarks or use non-contact targets, it is simple to get distortion measurements of a particular spot on the to-be-measured object in all three dimensions.

For space deployable antennas, often there is a need to measure how well the motion of a particular mechanism repeates.[15] Photogrammetry can easily measure the repeatability of end-stops and commanded positions. These measurements can be used to determine the hysteresis and positional errors of the internal sensors. The targets can be placed on a wide variety of surfaces to give a three-dimensional measurement of the differences between object positions.

As mentioned before, it is possible to apply photogrammetry technique philosophy to online measurement and hence real-time active control of telescope structure and antenna panel, since real-time inspection and recognition issue can be converted to the 3-D measurement of an object under inspection. A promising concept for a system for measuring the surface of the Large Adaptive Reflector (LAR) and structure of ELT has emerged.[7,14] This concept is based on simple triangulation methods used by photogrammetry technique but takes advantage of the properties and accessibility of the reflector panels to measure points on the surface without the need for a laser device. A CCD camera and at least 4 measurement points per panel are employed to measure the surface to an accuracy of about 200 microns over a range from 2 to 12 meters. Structurally, it seems evidently impossible to adopt 'above-the-surface' measurement scheme. Thus, the measurement system below the surface is a good alternative. Although there are restrictions on the capability of any particular measurement device to see multiple panels due to the backup structure and actuators as well as the geometry of the surface through its entire range of actuation. It is possible to directly measure one or more points on the back of each panel and operate them in groups. By setting measure points on the triangular backup structure, it is possible to monitor the structure deformation during operation to actively compensate for it to some extent by actuators to relieve final precise surface adjustment.

7. CONCLUSIONS

Photogrammetry technique has wide potential to be used in the astronomical telescope field. In general, specific applications of photogrammetric technique to astronomical telescopes would be antenna panel measurement, panel positioning, active surface controlling, thermal distortion monitoring, structural gravity static deformation monitoring and active compensating for sub-millimeter and millimeter radio telescopes, and even deployment repeatability measurements for space antennas. It is also promising for future extremely large optical telescopes. It will be a great tool if a real-time measurement is implemented. Further, research trends such as non-contact targeting technique, automating and optimizing sensor placement and the need for a common standard for the evaluation of optical coordinate measurement systems are undergoing. Actually, based on common video-camera, a so-called videogrammetry has emerged as a very popular measurement tool for industry. [13] If videogrammetry can offer high enough measurement accuracy, together with ready commercial photogrammetry software packages, it is of potential significance to make photogrammetric application to astronomical telescope more economic and efficient.

REFERENCES

1. B. D. F Methley, *Computational models in surveying and photogrammetry*, Blackie, Glasgow, 1986.
2. K. Edmundson and L. Baker, “Photogrammetric measurement of the Arecibo primary reflector surface”, *Coordinate measurement systems committee conference*, Albuquerque, 2001
3. S. Umeyama, “Least-squares estimation of transformation parameters between two point patterns”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 13, No. 4, pp. 376-380, 1991.
4. F. Schwab, *Private communication*, 2004.
5. Jingquan Cheng, *Principles of astronomical telescope design, from radio, infrared, optical, X-ray to Gamma ray telescopes*, Chinese science and technology press, 2003.
6. Dehua Yang and Jingquan Cheng, “Current Projects and New Initiatives for Radio Telescopes”, *ACTA ASTRONOMICA SINICA*, Vol. 44, Suppl. Feb. 2003.
7. Brent Carlson, “Geometry Study and Simulation of a Laser-Free Surface Measurement Technique for the Large Adaptive Reflector”, Oct. 1998.
8. F. Chen, G. M. Brown and M. Song, “Overview of three-dimensional shape measurement using optical methods”, *Opt. Eng.*, Vol. 39, No.1, pp.10-22, Jan. 2000.
9. http://www.geodetic.com/Downloadfiles/Basics of Photogrammetry.pdf.
10. http://www.alma.nrao.edu/projectbk/construction/chap4/chap4.pdf
11. Kenneth Edmundson, Lynn Baker, “Photogrammetric measurement of the Arecibo primary reflector surface”, *Proc. of the Coordinate Measurement Systems Committee Conference, CMSC*, Aug. 2001.
12. Paul Goldsmith, “Resetting the Arecibo Primary Reflector Surface”, *The Arecibo Observatory Newsletter*, No. 32, pp. 1-4, Mar. 2001.
13. Giuseppe Ganci and John Brown, “Developments in Non-Contact Measurement Using Videogrammetry,” *Boeing Large Scale Metrology Seminar*, 2000.
14. Guoping Li and Dehua Yang, "Preliminary structure design and analysis of the Chinese Future Giant Telescope", to be presented on this conferece.
15. Michael Wiktowy, Mark O’Grady, Gary Atkins and Raj Singhl, “Photogrammetric Distortion Measurements of Antennas in a Thermal-Vacuum Environment”, *CASI*, Vol. 49, No. 2, Jun. 2003.
16. R.S. Pappa, L.R. Giersch and J.M. Quagliaroli, “Photogrammetry of a 5M Inflatable Space Antenna with Consumer-grade Digital Cameras”, *Experimental Techniques*, Vol. 25, No. 4, pp 21, Jul. 2001.