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STUDY OF OPTICAL TECHNIQUES FOR THE AMES UNITARY WIND TUNNELS PART 4. MODEL DEFORMATION

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PART 4. MODEL DEFORMATION

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Summary

A survey of systems capable of model deformation measurements have been conducted. The survey included stereo-cameras, scanners, and digitizers. Moiré, holographic, and heterodyne interferometry techniques were also looked at. Stereo-cameras with passive or active targets are currently being deployed for model deformation measurements at NASA Ames and Langley Research Centers, Boeing, and ONERA. Scanners and digitizers are widely used in robotics, motion analysis, medicine, etc., and some of the scanner and digitizers can meet the model deformation requirements. Commercial stereo-cameras, scanners, and digitizers are being improved in accuracy, reliability and ease of operation. A number of new systems are coming into the market.

Introduction

In order to achieve the full-scale airplane Reynolds numbers, todays wind tunnels operate at high pressures and low temperatures. Examples are the NASA National Transonic Facility and the European Transonic Wind Tunnel which operate at 9 and 4.5 atmospheres respectively. Both can operate at liquid nitrogen temperatures. These high pressures subject the model geometry, particularly the shape of the wing and control surfaces to large aeroelastic distortions. Even for facilities like the NASA Ames Unitary Plan Wind Tunnels operating at a couple of atmospheres, substantial model deformations do occur. Unless the wind tunnel data are corrected for the model deformation, the stability and performance of the airplane will be influenced. Recently a new "pressure sensitive point" technique for measuring model pressures requires model deformation data. In this technique, "wind-off" model shape is superimposed on the "wind-on" shape to obtain the model pressures. In order to get accurate pressure data, the "wind-on" deformed shape must be known.

A number of model deformation sensing techniques have been investigated during the past two decades. These techniques are optical and remote sensing techniques because of the nature of the wind tunnel. Moiré contouring, scanning heterodyne interferometry, holographic contouring and stereo-photogrammetry have been considered. The stereo camera approach seems to best meet the model deformation requirements. A generation of stereo camera starting with film cameras, then video cameras, and finally with solid state cameras have been developed. The solid state cameras include linear photodiodes, area photodiodes, and lateral-effect detectors. The cameras typically measure targets located on the model. Both "active" targets using spots of lights and "passive" targets using ink and paint spots have been used. Software to calculate the 3-D coordinates of the targets have been developed and are basically based on triangulation.

From the fields of robot vision, robot guidance, orthopedics, and motion analysis, various types of 3-D measurement systems have evolved. Basically, three different principles were used; interferometry, radar or time-of-flight, and triangulation. Moiré interferometry systems with laser light are very accurate for measurement of very small variations such as surface deformations due to stress. Radar systems are typically used for measurement of large distances, but provide only moderate accuracy. For measurement of object at close range, such as models in wind tunnels, light spot projection systems using triangulation offer the best potential for accuracy.

Light projection systems based on projection of a single laser beam are more accurate than systems projecting multiple beams, single and multiple sheets of light. These multiple projection systems have faster acquisition speeds.

Recently, a number of commercial 3-D digitizers have been developed using light project of single and multiple laser beams. These digitizers offer speed, accuracy, and capability to display the images.

Purpose

The purpose of the study is to review optical sensor systems and optical techniques that are suitable for wind tunnel model deformation measurements. Emphasis will be placed on systems that can operate in a large wind tunnel environment. Special attention will be given to commercial products designed for "turnkey" operation.

Requirements

The model deformation requirements are based on the model size, sting and floor support, window size and configuration of the Ames 11 x 11, 9 x 7, and 8 x 7 wind tunnels. Other requirements are based on the tunnels' temperatures, pressures, and vibrations. Finally, low cost, low maintenance, ease of operation, and speed are considerations.

measurement areas	3x3 feet (sting models)
	3x6 feet (floor models)
measurement points	50 to 100
maximum deflection	3 inches
accuracy	0.003 inch
optical range	4 to 8 feet
temperature	40^o to 140^oF
pressure	0.1 to 2 atmospheres
vibration	± 0.002 inch at 30 Hz

Stereo-photogrammetry

The fundamentals of stereo-photogrammetry are given in textbooks by Slama[1], Horn[2], and Schalkoff[3]. Basically, it involves recording a scene from two views and the computation of the coordinates of the scene. The recording with cameras converts the 3-D scene onto the 2-D image planes of the camera, see figure 1. The computational problem is to calculate by triangulation the 3-D coordinates of the object from measurements of the 2-D images recorded by the cameras. Schalkoff[3] breaks the process into three parts.

1. The perspective-projective transform. These are the mathematical equations developed to relate the coordinates of points on an object to its coordinates of the images points on the camera image planes, see figure 2. Also shown are the various coordinate systems. The direct linear transformation[4] is a commonly used transform that is a linear relationship between coordinate of points in the

camera plane and the corresponding object space coordinates. Schalkoff[3] , and Laurich[5] have derived transforms that allow the measurement of object points with respect to an arbitrary coordinate system. Of particular interest is the transformation to the model coordinate system.

2. The "correspondence problem": The need for correspondence data in inferring 3-D object points from multiple images. In other words, a matching of points in the images is required. Figure 3 is an illustration of 3 points A, B, C and their corresponding images in the left and right cameras. A problem would arise in matching if one camera does not see all three points and it would be difficult to identify the corresponding object points and their images. This has led to "active" targets or lights that are sequentially turned on or special light patterns that makes matching possible.

3. The need to know camera orientation parameters. The triangulation process to find the objects coordinates requires the "base line" or distance between the stereo cameras and the aiming angle of the cameras. This leads to the topic of camera calibration. "Pre-calibration" in the laboratory or "self-calibration" in the test site are two methods used to calibrate the camera systems.

<u>Stereo-Photogrammetry with Passive Targets</u>

1. Stereo-photographic System

Brooks and Beamish[6] describe a stereo-photographic method to measure aeroelastic deformations of airplane models in the wind tunnel. The stereo system uses two 70mm non-metric cameras mounted under the tunnel. The cameras were positioned to cover most of the model and all of the targets. In order to sharply focus the pictures of the targets, high-intensity high-speed electronic flash lights were used. This minimizes effects of model oscillations and allows the camera lens to operate at maximum f number for maximum depth of field over the angle of attack range.

The optical targets are "passive" targets in that external lighting is used to see them. They were made by drilling shallow 0.045 inch holes on the model surface and filling the holes with white plastic. The background was painted to a flat grey to make the white targets stand out. The targets appear as a 0.003 inch white spot on film. Over 100 targets were put on the model, 14 of the targets were on the fuselage and near the in-board section of the wing. These 14 targets are to be used as reference points in the Direct Linear Transform equations.

Since non-metric cameras are used, it is not necessary to measure camera position coordinates or aiming angles. This system also does not require the camera to be fixed between stereo pairs of photographs taken between wind-off to wind-on conditions. With the assumption that the 14 reference targets are rigid model points, the deformated points are measured relative to them. In a sense the reference target allows a "self-calibration" for every picture.

The data reduction process is done manually and can take hours. A comparator is used to measure the target coordinates on the film. The space coordinates for each target were computed in relation to the rigid reference targets by the Direct Linear Transform method. This was done for both wind-off (no aerodynamic load) and wind-on photographs. The deflections of each target due to aerodynamic loads is the difference in values for each individual target, wind-off and wind-on.

To test this stereo system, measurements were made to determine its accuracy by comparing stereo photograph data with dial gage data under zero loads, i.e. no model deformations. Typical accuracies of 0.005 were observed. This amounts to a wing twist accuracy of 0.1 degree near the inboard section of the wing and 0.2 degree near the wing tip. The test was repeated in the wind tunnel at transonic speeds at 4 and 8 degrees angle of attack. Due to model motions, test setup, the accuracy drops to about 0.02 inch.

2. Stereo-video Camera System

A video-based model deformation system was built by Burner, Snow, and Goad[7,8] for the NASA National Transonic Facility. Video cameras were used instead of film cameras due to inaccessibility of the cameras which were located in the plenum of the tunnel. There was a considerable loss of resolution by going to the video. The video cameras were high resolution 875 scan rate cameras. Reseau marks on the image tube faceplates were used to assess distortions. Quartz halogen lamps were used for lighting. Recording of the video images were made with a video hardcopy unit which prints the images on dry silver paper. The hardcopy was manually read with a high resolution comparator and the target coordinates stored for computer processing. The manual readup takes about 30 minutes per image pair. For the situation when tunnel vibrations or model dynamics prevent the use of the video hardcopy unit, a high resolution video disc recording up to 125 video image pairs is used. Hardcopies are made later.

The camera orientations can be found with either a calibration jig with 40 known targets or with a space resection method using model targets. The calibration was done at no flow in the tunnel for a range of model pitch and roll angles that bracket those of interest. This type of calibration method requires the cameras remain fixed between calibration and during the test. Note that this method does not require the rigid target assumption of Brooks and Beamish. The targets were made by painting small spots with fluorescent paint on the model surface. The data reduction followed that of Brooks and Beamish. An additional transformation was made to account for model pitch and roll. Lens distortions were also corrected.

Tests were conducted in the NTF at both ambient and cryogenic temperatures with a Pathfinder model. Experimental scatter was within 0.02 inch. Wing tip deflections were around 3 inches. There were vibration effects on the video camera and it was anticipated that for more severe tunnel conditions, this may become a serious problem.

3. Stereo-CCD system

A few years later, a solid state CCD camera with an IBM image acquisition system[9] was developed to replace the video-based one for the NTF. The CCD camera is less prone to vibration and digitization replaces the manual comparator reading of image coordinates. The CCD array was 752 pixels by 480 pixels. Two frame grabber boards were ganged together to allow simultaneous capture of the images in 1/3 seconds. In order to get the required accuracy, the pixel spacing must be known better than those given by the manufacturer's specification. Therefore, a reticle pattern was used to measure the pixel spacings. The lenses were also calibrated so that lens distortion can be corrected.

The procedure used to determine target coordinates is based on finding the centroid of the target. In order to accurately compute the centroid, a thresholding scheme was used to remove the background grey levels. The solution to the "correspondence problem" was to find the approximate target locations in terms of the pixel coordinates by either: (1) a manual setting with a video cursor to form a pixel coordinate file (this assumes the operator knows the target pattern) or (2) use an old centroid file with pixel coordinates of the targets with the same numbering scheme and overlay it on the current images. After the new target locations are calculated, it can be displayed to ensure that targets on the model are matched on both images. The transforms and triangulation necessary to find the model deformations are computed by the method described in reference 8.

A Pathfinder model was used to determine the accuracy of the system in the NTF. The tests were conducted at zero velocity to avoid flow uncertainties and to allow verification of the measurements with dial gages. The cameras were separated 36 inches and were 72 inches from the center of the wing. The calibration to find the camera locations and aiming angles was done with the model at zero angle of attack. The wing was then deflected mechanically with a jack so that the wing tip was deflected about 0.2 inch. Deflection data were taken at both 0^o and 4.3^o angle of attacks. The accuracy of the system was under 0.005 inch. It was found as before that deflection accuracy is highly dependent on the model roll angle. This CCD stereo camera model deformation system is the one that is currently being used at Langley Research Center.

4. Long-Range Stereo-CCD System

Meyn[9] is currently developing a two camera stereo system for angle of attack, vortex tracking, and model deformation for the NASA Ames 40 x80 x 120 Foot Wind Tunnel. It is a low cost system using a solid state CCD camera with 488 by 754 pixels, a Macintosh computer, frame grabbers, and a VHS video tape recorder (see figure 4). Hardware costs are around $30,000 and the development program started a couple of years ago. The software to operate the cameras and to calculate the target coordinates was done in-house.

The system requires manual selection of the calibration points and identify the stereo pairs. Calibration is done with a calibration frame made of 3 inch white balls attached to ropes hung from the ceiling, see figure 5. Note that the left and right cameras does not see all of the same targets which serves as an illustration of the "correspondence problem."

The initial tests were to determine the angle of attack of a 45 foot parafoil. The targets were 30 by 36 inch patches of white cloth sewn on to the parafoil. For steady motions, the system works well. The uncertainty in the angle of attack was less than 0.6 degree. For unsteady motions of the parafoil, the system does not capture and store the images fast enough to see the dynamic motions. The lesson learned was the need for very accurate calibrations and the need to correct for lens distortions. To get better accuracy, sub-pixel resolutions are required.

5. Bio Vision System

Bio Vision is a commercial system that was developed for analyzing human motion. One of the current applications is to measure the golf swing. The system can use up to six CCD cameras to view the object. Sofware digitizes the images and displays it on a Silicon Graphics system. The accuracy is about 0.1 inch but this could be improved to meet the model deformation requirement with further development. Estimated cost of such a system would be around $250,000.

<u>Stereo-Photogrammetry: Active Targets</u>

1. Stereo-Electro-optical Tracker System

The Stereo-Electro-Optical Tracker System[11], SETS, was built about 10 years as a model deformation for the NTF. This is a complex system designed for rapid operation which uses light emitting diodes as the active targets. SETS uses four trackers, see figure 6 and up to 63 LED targets embedded in the model, and computers to synchronize the LED with the trackers and data processing.

The operational scheme, figure 7 is to search for a target based on its previous location. Once the tracker locates the target, it locks onto it and reports the location to the computer. The computer has a target interface unit, TIU, which controls the targets to be viewed, turns on the targets in sequence, and commands the tracker to start their search and to track them. After the target is found by the trackers (or reaches a preset time limit), the TIU starts the cycle for the next target. Since only one known target is being measured at a time, there can be no confusion about which target is being measured, i.e. it solves the "correspondence problem."

The tracker uses an ITT Electro-optics image dissector tube as the detector. This tube is an electronically pointed photomultiplier which converts the optical image into an electronic image. The electronic image can then be accurately and rapidly pointed by a magnetic field through an aperture to filter out reflections from the LED. The electronic image is analyzed and converted into digital form and sent to the computer for computation of target coordinates.

SETS was tested in the laboratory. A number of problems associated with the complexity of the system and the image dissector tube occurred. In the meantime, CCD technology improved substantially and SETS which cost about 1.6 million dollars was never deployed in NTF. NTF currently uses a CCD stereo system. A brief history of the development of model deformation measurement for the NTF was given by Holmes[12].

2. Selspot System

Selspot System Ltd. produces a commercial 3-D measurement system that could be used for model deformation. It has been used by General Motors[13] for robot guidance, and by the National Research Council of Canada[5] to measure displacement, velocity, and acceleration of model ships. The system consists of two cameras, a computer that strobes the LEDs, adjust its intensity, and calculates target coordinates, figure 8. The camera uses a lateral-effect-pnotodetector to measure the position of the light spot from the LED. The advantage of using this type of detector is that x and y coordinates of the light spot is determined by two current outputs, figure 9. The problem of this detector is that it cannot distinguish between the target and its reflections. The General Motors system installed infrared band-pass filters to try to solve this problem. Ambient lights also affect the detector. The General Motors experience showed that unwanted reflections were a serious problem. For example, the system accuracy of 1.5mm dropped to

8mm whenever the operator stood in the field of view of the cameras. It was also found that any errors in calibration are propagated into the measurements.

3. Eloptopos System

Eloptopos is a commercial stereo-opto-electronic system build by the Swedish firm Eloptricon and later by Saab for angle of attack measurements in wind tunnels and for model ship motions in hydraulic basis. It is designed to be a highly automated system that controls the system startup, checks for malfunctions in the camera controls, and read and compensate for background light levels. LEDs with fiber optics create a small target. The camera uses a linear photodiode with 1048 pixels. A cylindrical lens converts the target image into a thin streak perpendicular to the linear array so that model movements are eliminated. A precise geometric survey is required to determine camera locations. Once done, no further calibrations are needed. Fuijkschot[1] of the National Aerospace Lab. of the Netherlands used this system for angle of attack measurements and found accuracies of 0.01° which translates to 0.16mm.

4. Altitude and Deformation Reconstruction and Measurement System

The French ONERA[15], is currently developing a stereo optoelectronic model deformation system called RADAC for the European Transonic F-1 Wind Tunnel. This tunnel operates at cryogenic temperatures and at pressures up to 4.5 atmospheres. RADAC can operate as a tracker like SETS with the LEDs lighted sequentially or as a stereo camera with all the LEDs lighted simultaneously. It is designed to operate in real-time. Target coordinates are computed with centroid detection and automated threshold processing fitted to the background light level. Two cameras are used. Each camera uses two linear photodiode arrays lined perpendicularly to each other. An invar beam is used to mount the cameras to minimize temperature effects. A calibration frame of known target locations is used to calibrate the cameras. It is designed to handle both sting mounted and floor mounted models of 1.7 meter span (as required in the NASA Ames 11 x 11 Foot Transonic Wind Tunnel). The cameras have a 60° angle of view. A remote control adjustment system was incorporated since test section plenum access if limited to a few times a year.

The system has been tested at a Mach number of 0.25 and 10° angle of attack. The wing tip of a transport model deflected 0.4 cm. It nearly met the design accuracy of 0.02 cm for an average wing twist of 0.05°.

5. Optotrack System

The Optotrack system introduced by Northern Digital Inc. in 1989 is a commercial 3-D real-time motion analysis system. It uses tracker technology to sense infrared LEDs operated in sequence. Up to 256 LEDs can be tracked. The system shown in figure 10 consists of LED targets, a system unit for target sequencing, cameras and a PC computer. Each camera uses vertical and horizontal aligned 2040 pixel linear photodiodes to sense the target. IR reflections from the target pose no problem since the image is digitized (see figure 11) and a thresholding scheme eliminates low-level interference from reflections and ambient lights. Target location is determined with a centroid algorithm. Two systems are available. The 2000 Series is a flexible 3-D motion system that uses two or more cameras. Accuracy is 0.1 mm in x and y and 0.15 mm in depth. It can cover a volume of 6 x 6 meters. Cost is $72,000. The 3000 Series is a precalibrated system, figure 12, that has a field of view of 1 x 1 m at a distance of 2 m. The accuracy is the same as the Series 2000. Cost is $57,500.

Boeing[17,18] used the Series 2000 in their transonic wind tunnel for model deformation measurements. Initial tests were encouraging although a number of problems arose. A bench top test indicated a position accuracy of 0.0006 inch at a distance of 6 feet. A calibration frame in the wind tunnel made the calibration a simple process. Vibration of the test section wall rails on which the cameras were mounted introduced significant errors.

6. Mapvision System

Mapvision II is a commercial photogrammetric machine vision system built by Oy Mapvision Ltd. of Finland for accurate close-range dimensions measurements. It is self-calibrating, programmable, and designed for ease of operation. Cost for a four camera system is about $80,000.

Moiré Contouring

Moiré interferometry is a technique that builds up a contour map of a three-dimensional surface. Moiré fringes are created when two matched gratings* are superimposed across the field of view. The fringes become lines of equal depth. The technique has been used to measure contours of equal deformations in stress analysis. Meadows et al.[19] has used it to contour a model airplane, figure 13. It has also been used to define the shape of 3-D objects for robotic applications. Techniques to generate contours and to automatically reconstruct the hologram have been studied by Cline, et al.[20] and Zelenka, et al.[21]. Hildebrand and Doty[22] proposed using Moiré contouring as a technique, see figure 14, for model deformation measurements in the NTF. Since the optical system must be located outside of the test section, a projection and receiving arm with gratings, lights, lens and camera are designed to project the beam onto the model and to view the fringes. An incoherent white light source was chosen instead of a laser because of speckle effects. An analysis was conducted on the effects of diffraction from the gratings and optics. Other factors studied included depth of focus, and noise. Since fringes are created from model vibrations as well as model deformations, the design of gratings that could eliminate model motions were considered. The main result of this study was Moiré interferometry is not accurate enough to meet requirements of model deformation. At a distance of 1 meter, the accuracy was a few millimeters, way short of the required tenth of a millimeter.

Scanning Heterodyne Interferometry: SHI

Hildebrand and Doty also investigated SHI for model deformation measurements. SHI is a form of optical radar that senses the phase change of a laser beam reflected from a surface. The basic concept, figure 15, consists of two lasers, a 2-D scanner and detectors. Two lasers operating at different frequencies to obtain the

* Footnote: Moiré fringes can be created by other methods. Hildebrand and Haines[23] proposed holographic methods with two identical lasers and two different wavelength lasers. Vest[24] proposed a Michelson interferometer, in fact any interferometer can be used.

required sensitivity are spatially mixed by the 1st beam splitter. The resulting beam is split by the 2nd beam splitter into a reference and probe beam. The probe beam passes through a 2-D scanner that directs the beam to the surface. Reflected radiation is picked up by the scanner. The distance from the scanner and the point on the surface is obtained by measuring the relative phase change of the reference and probe beams. Knowing the scanner pointing angle and the distance, the 3-D coordinates of the point is found.

A laboratory experiment was conducted to test this concept. To eliminate the alignment problem of two laser beams, one laser with a modulator was used (see figure 16). A laser diode provided the light source and a photomultiplier, PMT, was used as the detector. A phase lock loop was designed to measure the phase change. The accuracy of this system was about 3mm which is not sufficient. The conclusion was model deformation accuracy necessitate phase measurement accuracy that is near or beyond that state of the art.

Contour Holography

The third scheme investigated by Hildebrand and Doty was holographic interferometry. The recording and reconstruction is standard, see figure 17. To generate contours, the hologram is exposed twice; first at one wavelength and a second time at a slightly different wavelength. In practice, the two exposures should be done simultaneously to eliminate vibrational effects of the object. The analysis showed that the difference in laser wavelengths should be 10 to 40 angstroms. Dye lasers can give the required wavelengths, but efficiencies are very low. The ruby laser can lase at 694.3 and 692.9 microns. Development of such a laser would require several years. It is believed that the program was not pursued.

Laser Scanners

Laser scanners with optical triangulation is a technique for acquiring high-precision 3-D images. There are now devices built using a single laser beam, a sheet of laser light, and an array of light dots. The single beam systems are the most accurate. The light sheet, multiple light sheets, and arrays increase the number of simultaneous measurements and hence the acquisition speed.

The basic principle of optical triangulation can be illustrated by figure 18. The laser beam is reflected by a rotating mirror and scanned on the surface. A camera consisting of a lens and a position sensitive photodetector measures the location of the illuminated point on the surface. By trigonometry the 3-D coordinates of that point are calculated. (This requires knowing the angle of the mirror, the baseline distances, b, and l', and the measured distance p. The scheme for optical triangulation using a light sheet and a mask are shown in figures 19, and 20, respectively. A paper describing some of the 3-D laser scanner systems is given by Blais et al.[25].

1. Synchronized Scanners

Rioux[26] has built several laser range finder systems based on synchronized scanners using a single beam. Figure 21 shows an autosynchronized geometry using multifacet pyramidal mirror. Figure 22 uses two sensors to minimize the shadow effects and allow the beam to reach holes. Figure 23 is a 360^{o} range camera. Figure 24 incorporates an acoustic-optic deflector in the camera. These systems illustrate some of the typical concepts being used. The typical laser used above is a 15mw HeNe laser. To minimize background light on the image, an interference filter is used. These systems can have a large field of view and good resolution.

2. Large Depth of Field Scanner

Rioux, et al.[27] built a large depth of field scanner for robotics. This compact unit is about 9 x 8 x 12 cm in size and weighs about 450 grams. The resolution is 7 mm at a range of 1 m. A sketch of the unit is shown in figure 25.

3. Compact Scanner

An example of a compact scanner is the one built by Nimrod[28]. It is based on synchronized transmitting and receiving mirrors to scan a laser beam, see figure 26. Typical accuracies are 0.07% at 1 meter range.

4. Structured Lighting and Mask Scanners

The use of structured lighting and mask to encode the 3-D data was investigated by Rioux and Blais[29]. A 15 mw laser was used to project an array of dots on the objects surface. A mask in front of the camera gives the range data. The principle of the mask for range measurement is illustrated in figure 20. When point A on the reference plane is in focus on the CCD sensor, point B, on the surface produces a circle of diameter b'b' when an annular-aperture mask is used. The diameter of the circles gives the range Z while the center of the circle provides the x and y coordinates.

An experiment was done with a 15 mw HeNe laser to project a structured light pattern of dots, see figure 27, on a stepped pyramid. Figure 27 shows the larger diameter circles near the center of the pyramid which is closer to the camera, and smaller circles as the steps on the pyramid are further away. The resolution of this system was better than 1 mm at a distance of 25 cm.

5. Cyberware 3D Digitizers

Cyberware Laboratory Inc. offers a 3D digitizer that is based on a laser light sheet from a low power HeNe laser. The object is viewed from two angles with mirrors. A precision CCD sensor digitizes the image and creates a rectangular range map - an array of distance measurements. The accuracy range from 0.004 to 0.020 inch. Ames has recently purchased a system and initial tests indicated an accuracy of about 0.004 inch. It can digitize about 15,000 range measurements per second. The data is transferred to a graphics workstation for viewing immediately. The scanning process is controlled by the computer to move motion platforms. Platforms to move the digitizer along a linear or cylindrical scan path are available. The linear scan is suitable for wind tunnel applications.

A picture of the Cyberware digitizer is shown in figure 28. It is about the size of a 13" monitor. The digitizer comes in both color and black and white. For model deformation measurements, color may be advantageous in that color targets painted on the model could be identified and individually digitized. The color system high sensitivity can accommodate varying lighting conditions and surface properties.

The cost of the digitizer is about $30,000. Motion platofrms vary from $5000 to $20,000. An Ethernet interface, $3500, and software for running on a Silicon Graphics workstation, $5000. The cost of the digitizer for wind tunnel at the Unitary would be higher due to custom features. Initial discussions with Cyberware indicated that the baseline distance between the viewing mirrors should be about 1 meter to get good accuracy. Low thermal expansion materials may be needed to mount the various components.

6. Cyber Optics Digitizers, Digibotics Scanner

There are several commercial 3D digitizers[31] that operate with single laser beams. The single beam system is inherently more accurate than the light sheet system. Cyber Optics offers such a product. This product works by projecting a light spot onto the surface and imaging the reflected light onto an array detector. The system calculates the centroid of the image spot. It uses imaging optics to keep the image in focus. This means the digitizer scan head must maintain a constant distance from the object. The Cyber Optics scan head has been used by Laser Deisgn Inc. for a 3D digitizer that has an accuracy of 0.00175 inch at a range of 6 inches. This system is priced at $167,000.

Digibotics offers a single point laser that can scan parts up to one cubed meter at an accuracy of ±0.005 inch. It uses a unique triangulation technique that does not require imaging optics. Cost is in the $50,000 range.

Recommendations

A: For model deformation mesurements, the first chjoice would be the systems that use passive targets. This eliminates the cost of instrumenting the model with active targets. Some models may not have space for active targets. At this time, three passive target systems should be investigated further.

1. One would be the NASA Langley stereo-camera developed by Al Burner. This stereo-camera has the required accuracy and has been used in a wind tunnel. However, the system does require manual intervention in some phases of the operation. There may be some difficulties in obtaining this system in that Langley may not have time to build one for Ames.

2. The Bio Vision system built in Palo Alto, California has the potential to meet the required accuracy. Efforts to test and improve the current model should be made.

3. The Cyberware camera is a good candidate for wind tunnel model deformation measurements. The accuracy will need to be

improved by a factor of two or more. The existing Cyberware camera will need to be re-designed for a much larger separation between the viewing mirrors. Other factors to be evaluated would include thermal expansion, space limitations and vibration effects. Ames has brought a Cyberware camera. A program to check out some of the above problems should be done.

B. The stereo camera using active targets that best meet the Unitary's needs is the one made by Optotrack. It has been tested by Boeing. Improved versions are now being marketed. Further investigations and demonstrations by Optotrack should be pursued.

C The other techniques, such as Moiré contouring, scanning heterodyne interferometry and contour holography does not seem to work for model deformation measurements.

D. The commercial laser scanners are being developed rapidly and new products are coming to the market. (Cyberware is the oldest product.) These systems should be followed closely for possible model deformation applications.

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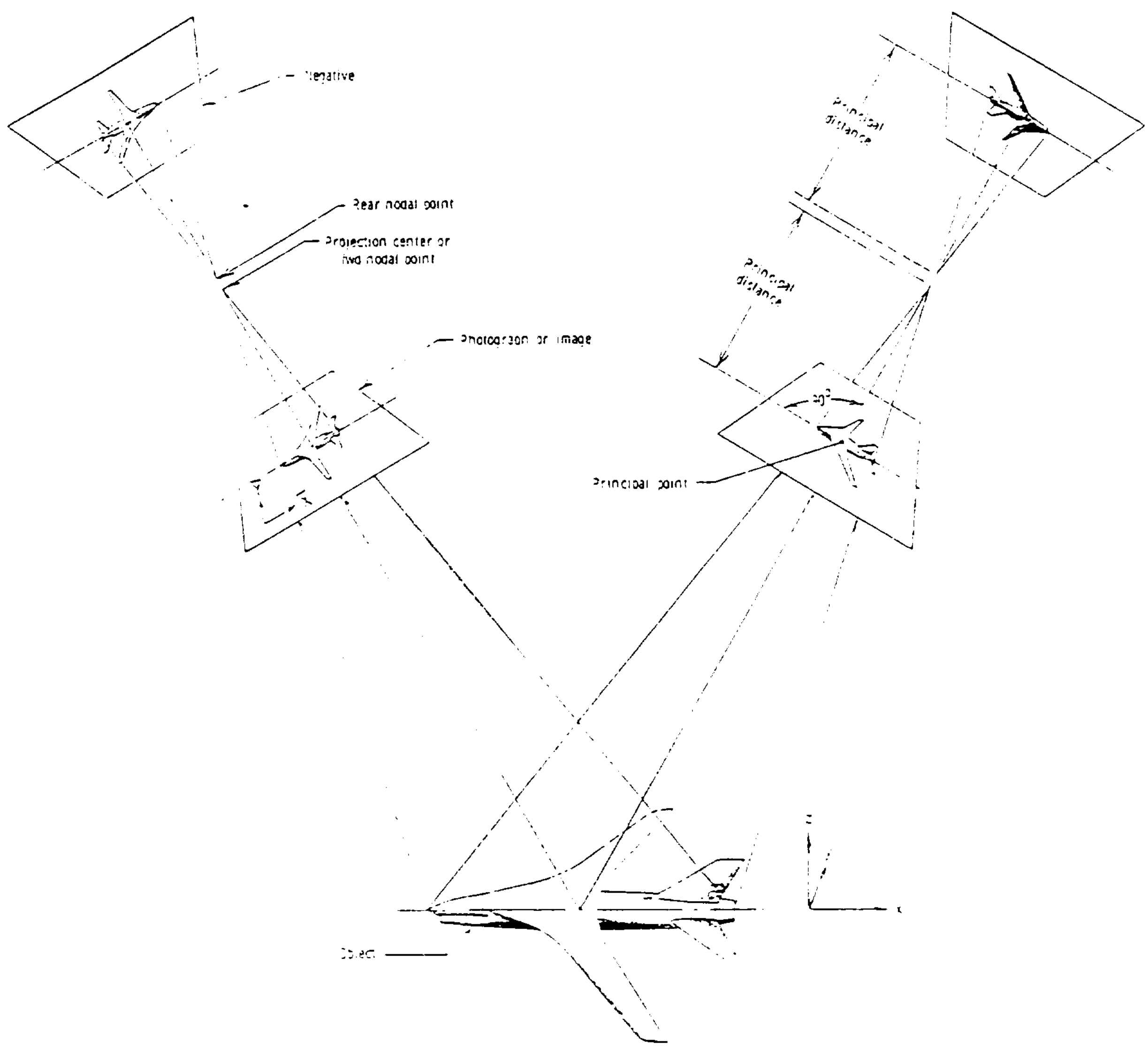


Figure 1. Sketch Showing Basic Photogrammetry Concepts. (after Brooks and Beamish)

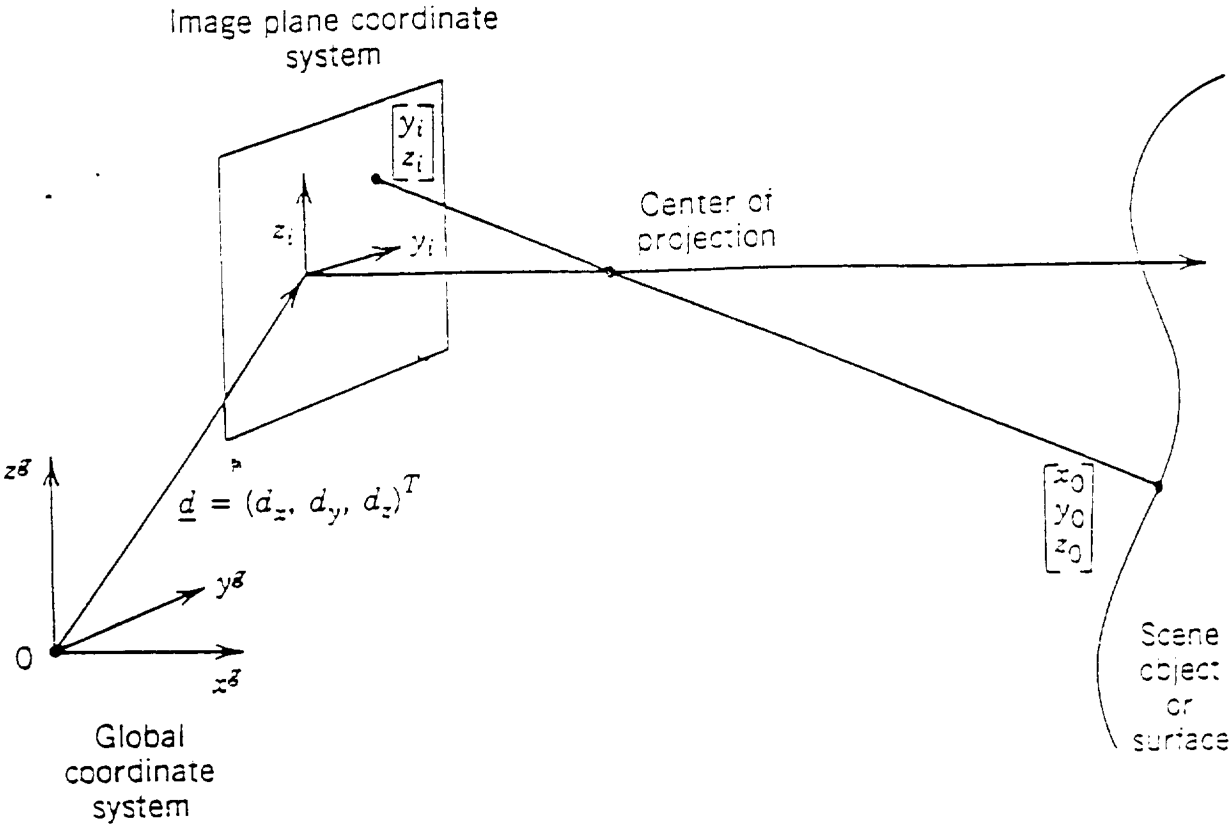


Figure 2. Global Coordinate System Offset from Image Plane. (after Schalkoff)

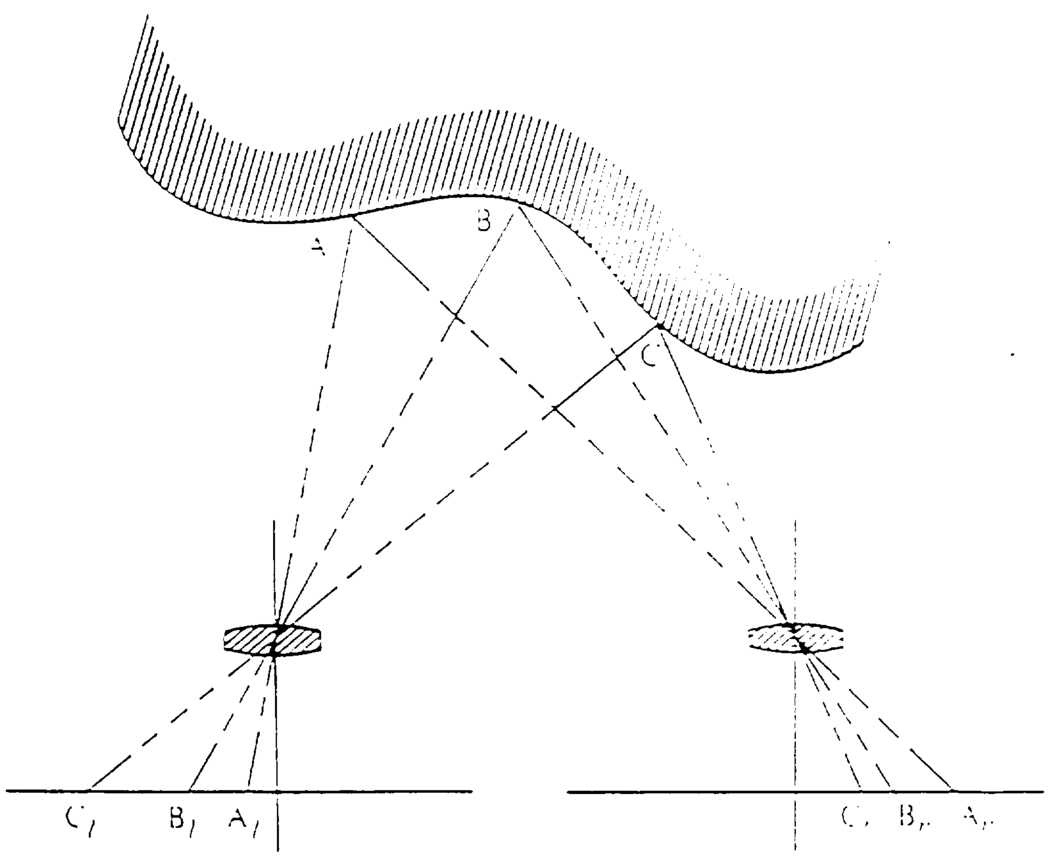
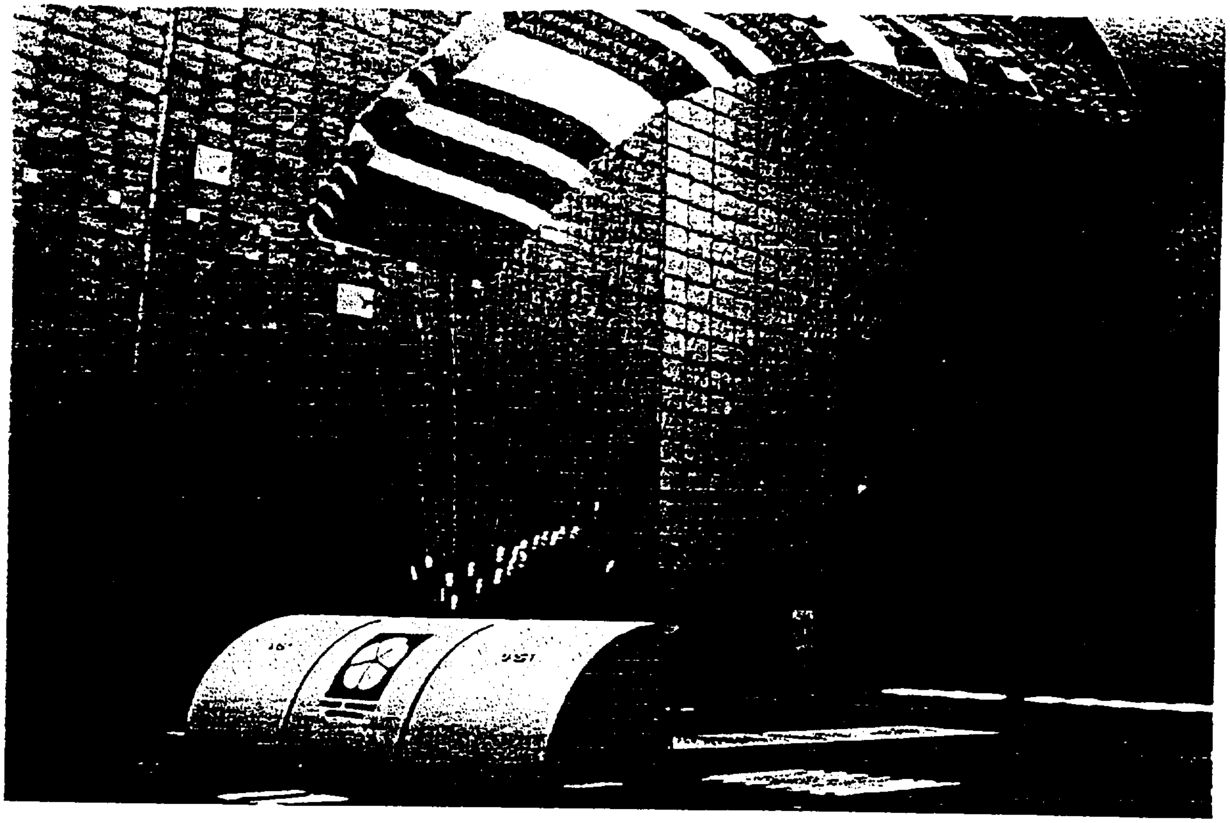


Figure 3. Sketch Showing the Corresponding Points. (after Horn)



Parafoil in the test section of the 80- by 120-Foot Wind Tunnel.

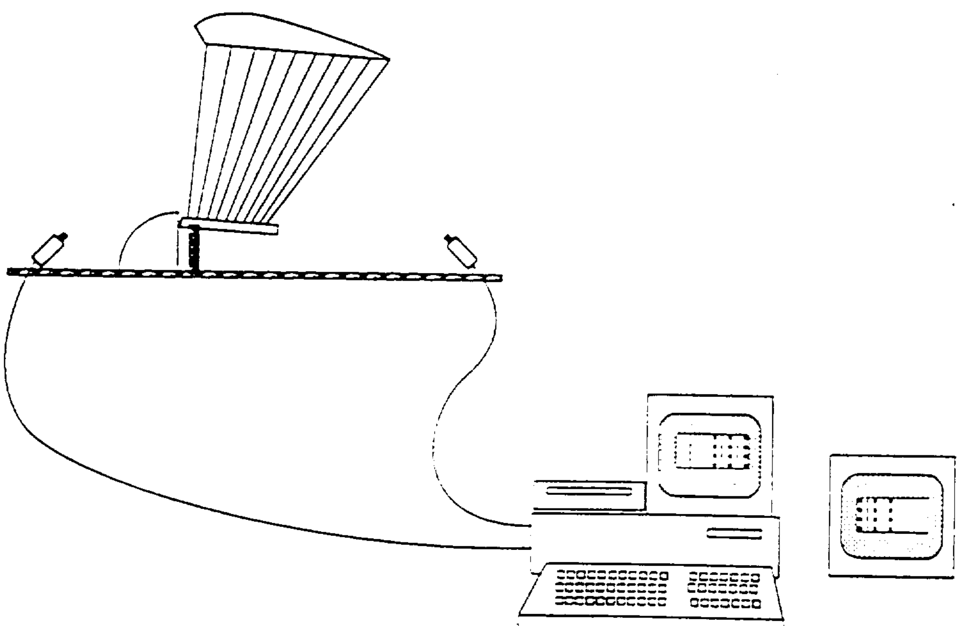


Figure 4. 80x120 Wind Tunnel Stereo-Camera.
(after Meyn)

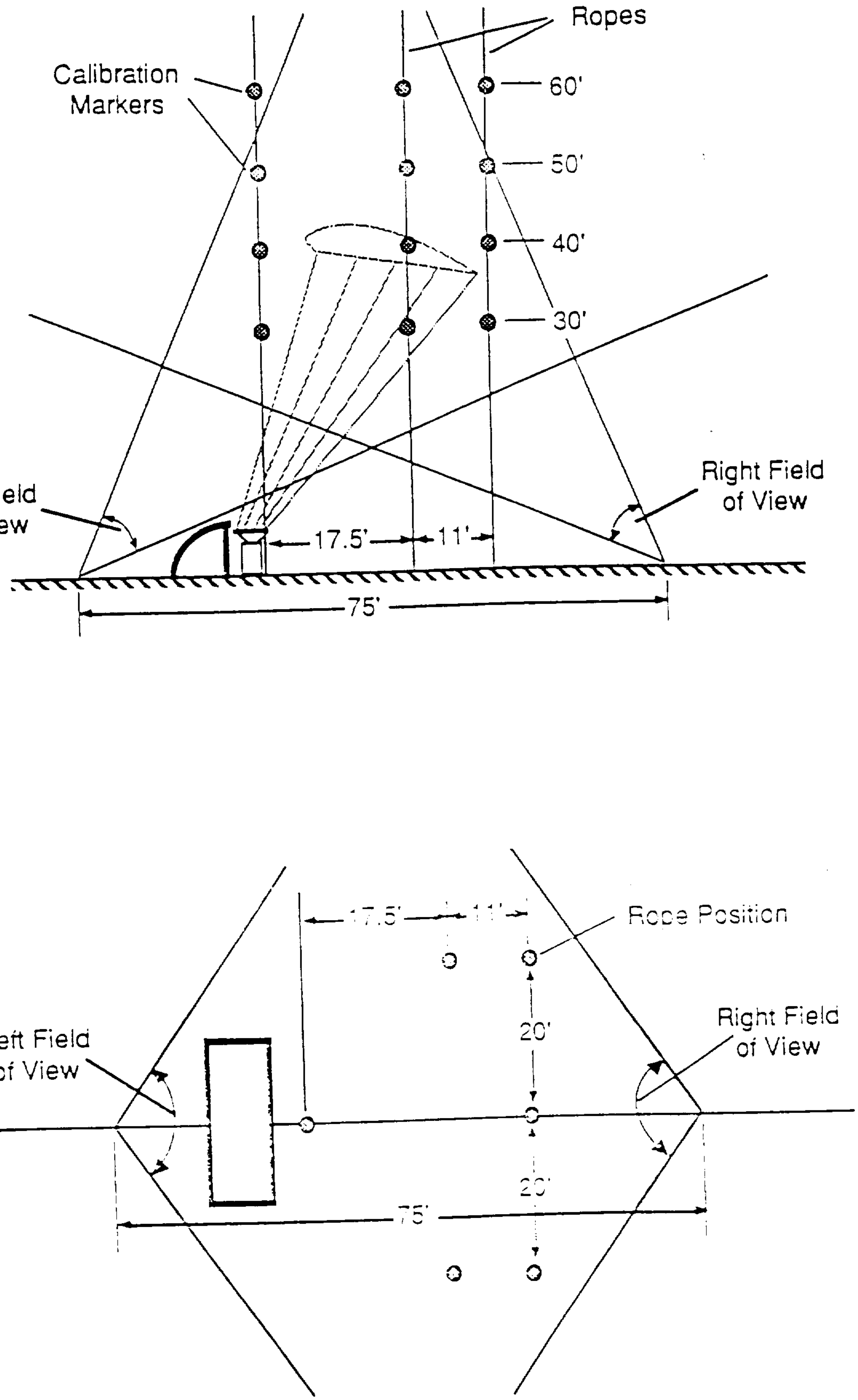


Figure 5. 3-D Calibration Grid.
(after Meyn)

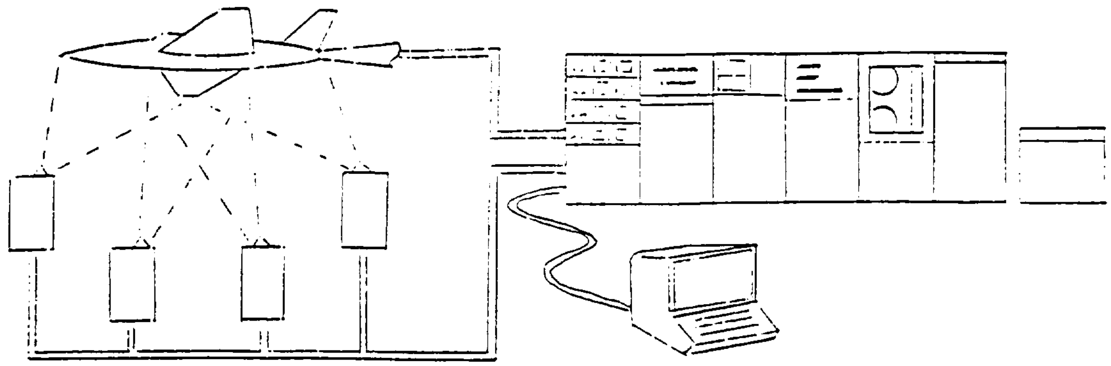


Figure 6. Stereo Electro-Optical Tracker System, SETS
(after Hoilman)

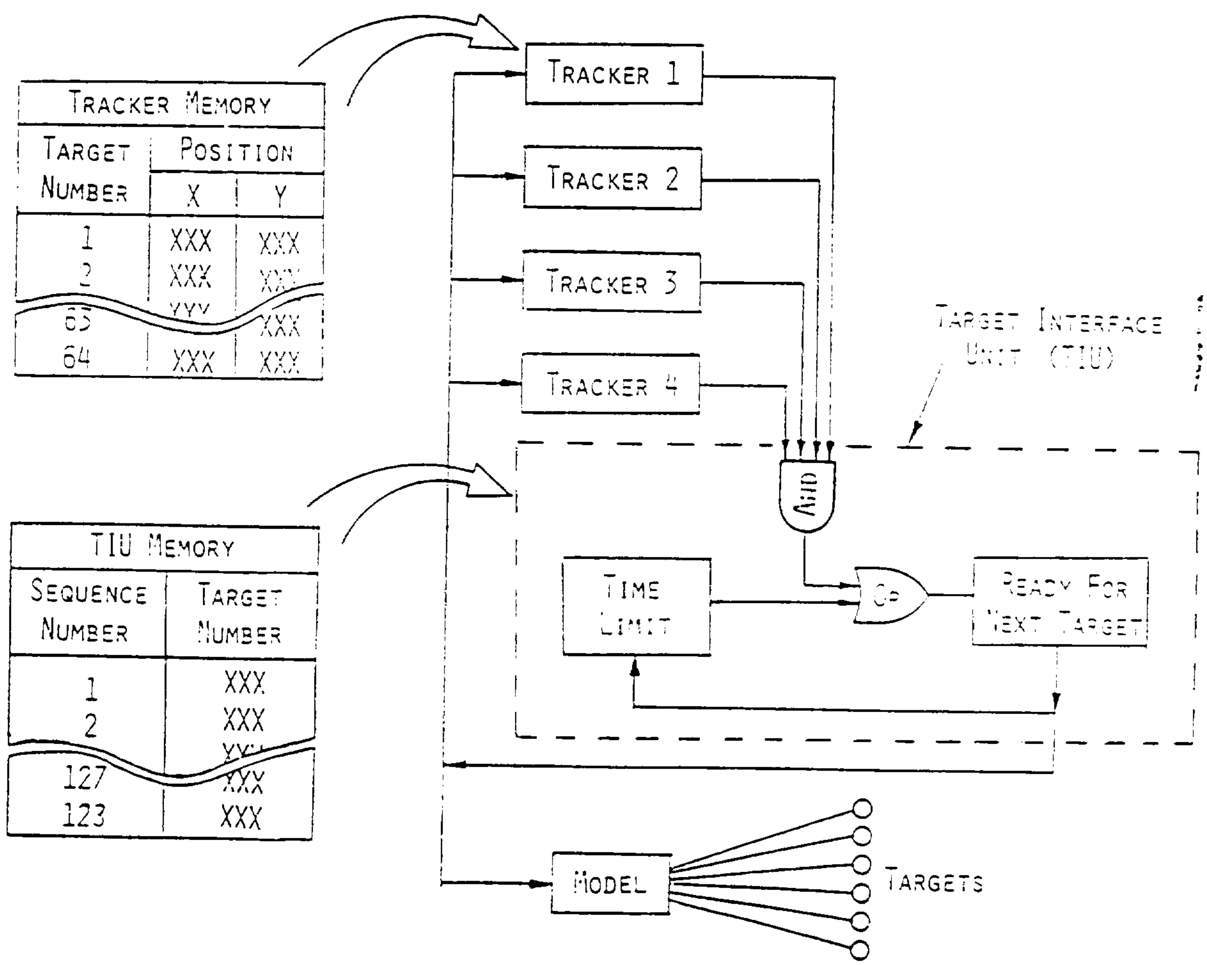


Figure 7. Operational Scheme for SETS
(after Hoilman)

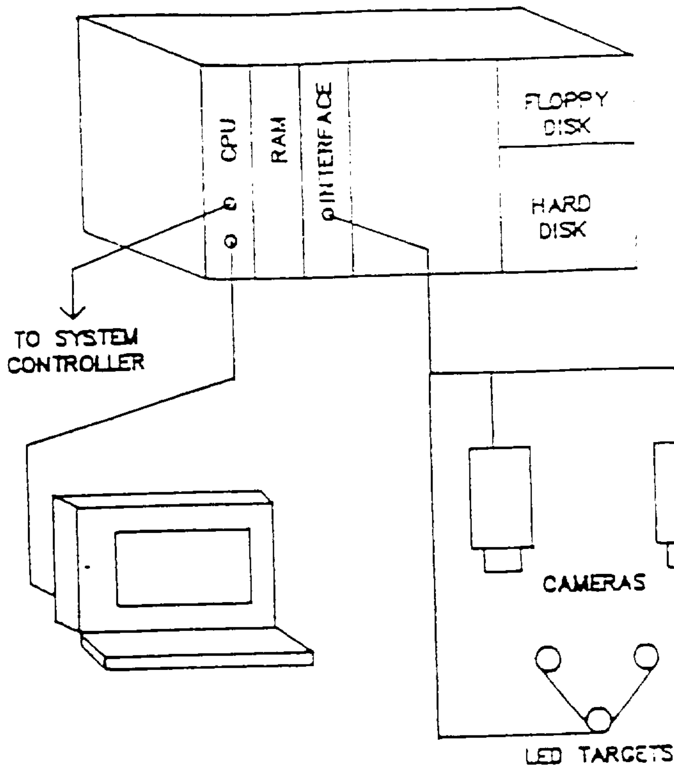


Figure 8. Sketch of Selspot System. (after George)

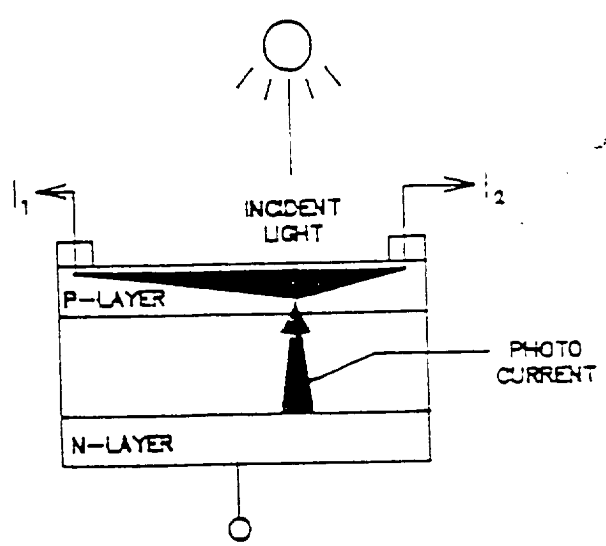


Figure 9. Sketch of a Position Sensing Detector. (After George)

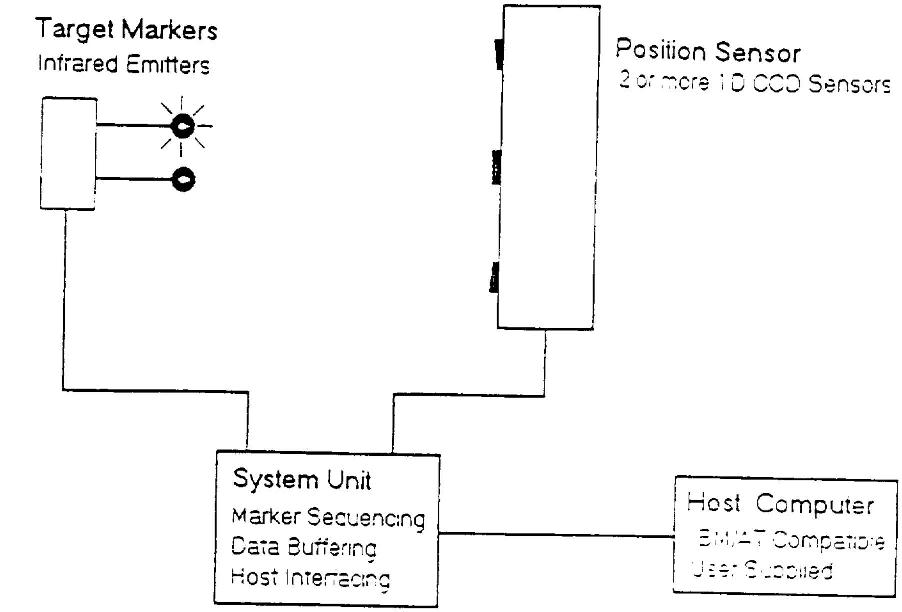


Figure 10. OPTOTRACK Operating Scheme.
(from OPTOTRACK Catalog)

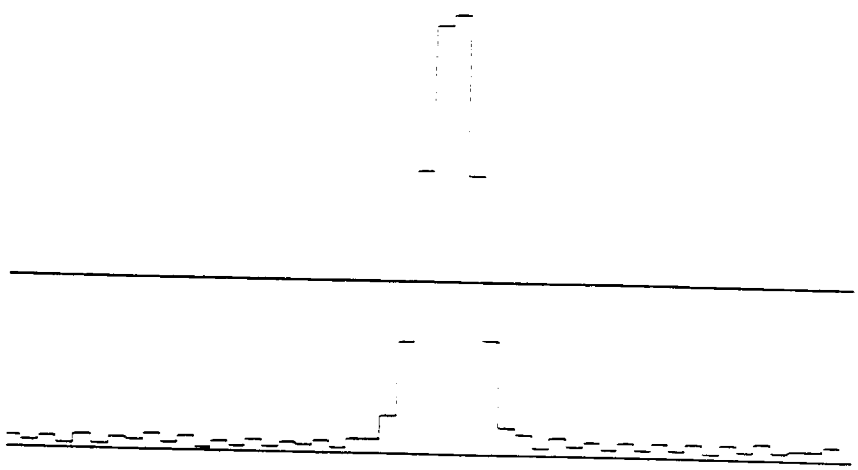


Figure11. Typical Waveform on OPTOTRACK CCD Sensor.
(from OPTOTRACK Catalog)

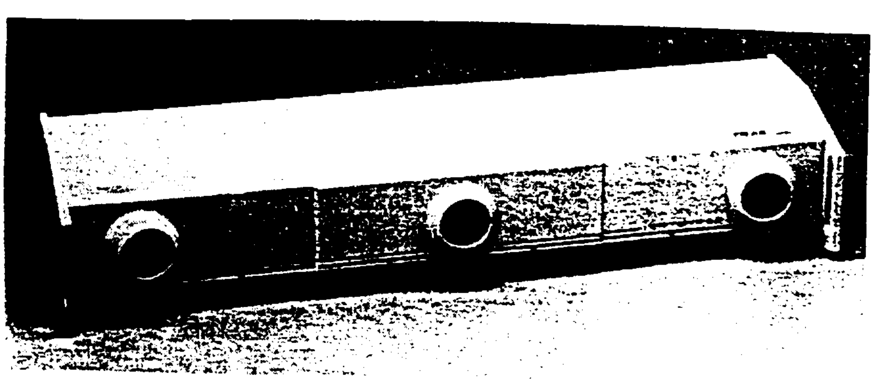


Figure 12. Photograph of OPTOTRACK/3000 Camera.
(from OPOTRACK Catalog)

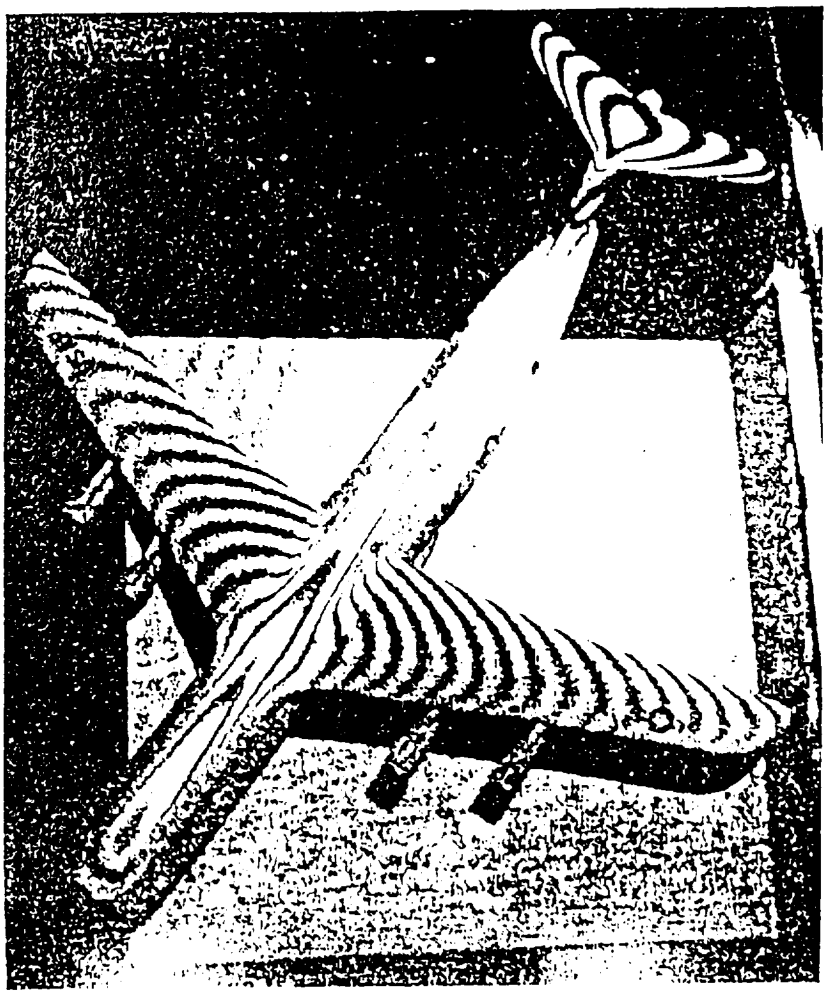


Figure 13. Moire Contours of a Model.
(after Medows)

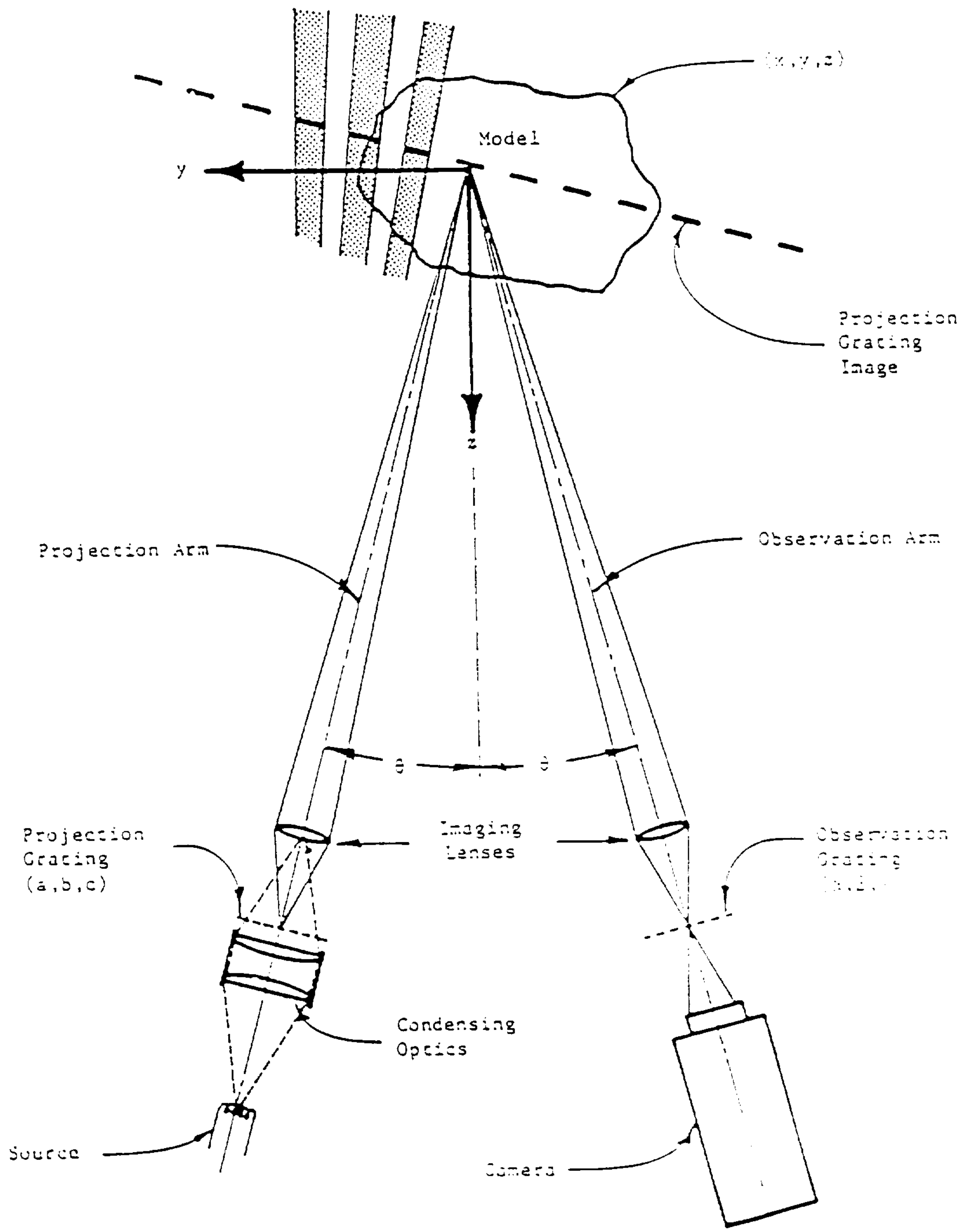


Figure 14. A System for Projection of Moire Contouring.
(after Hildelbrand and Doty)

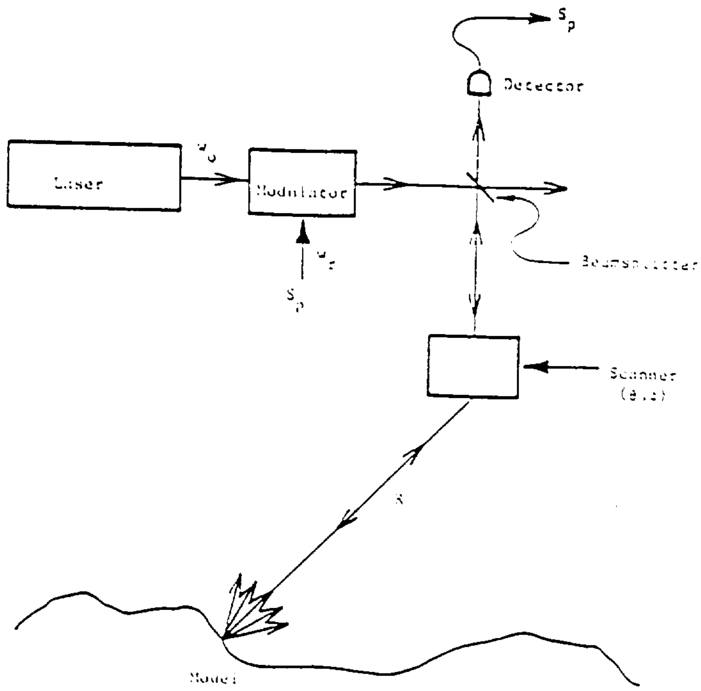


Figure 15. Scanning Heterodyne Interferometry Scheme. (after Hildebrand and Doty)

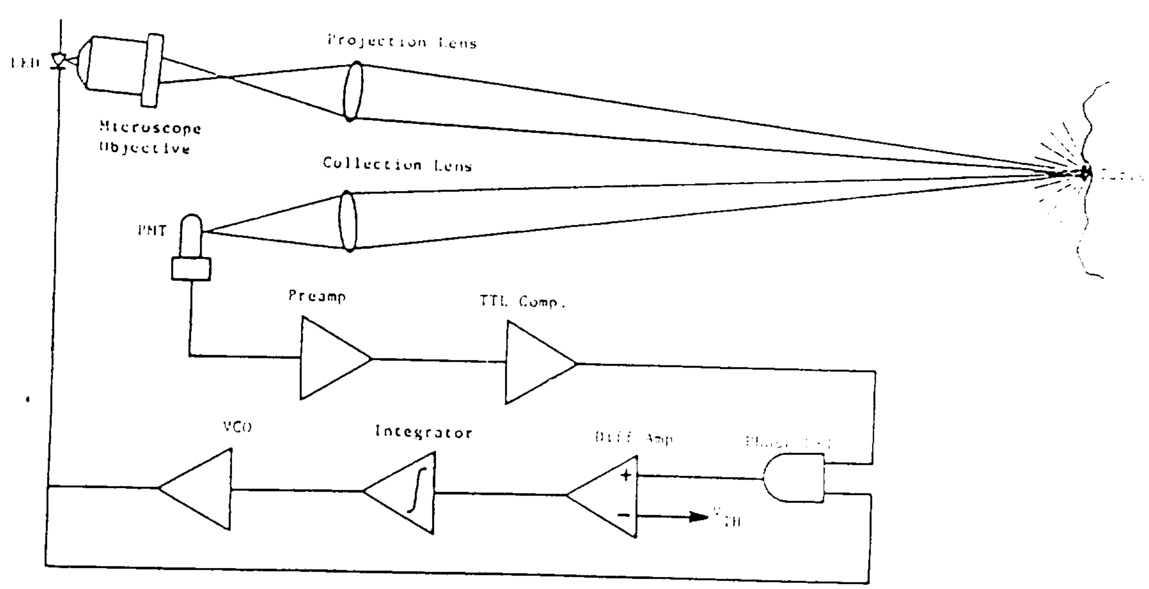
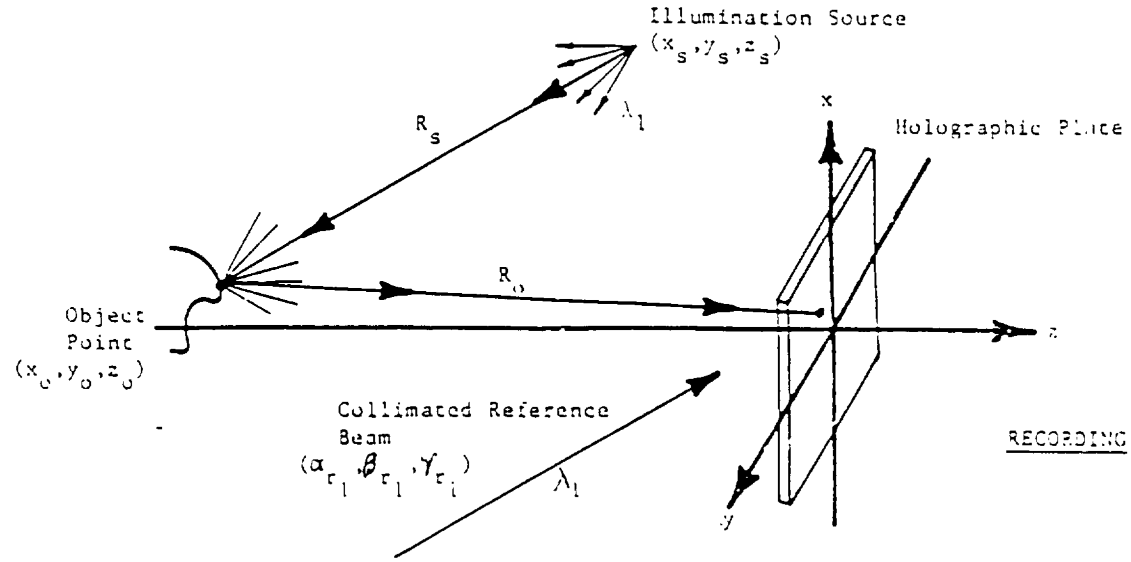


Figure 16. Scanning Heterodyne Interferometry Mock-up. (after Hildelbrand and Doty)



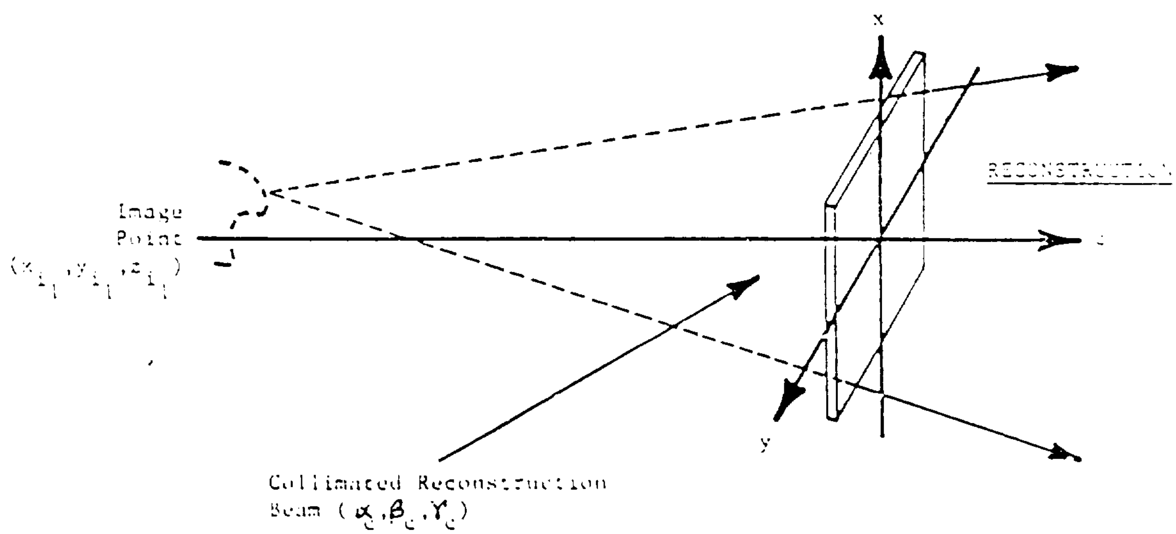


Figure17. Recording and Reconstruction of Holograms. (after Hildelbrand and Doty)

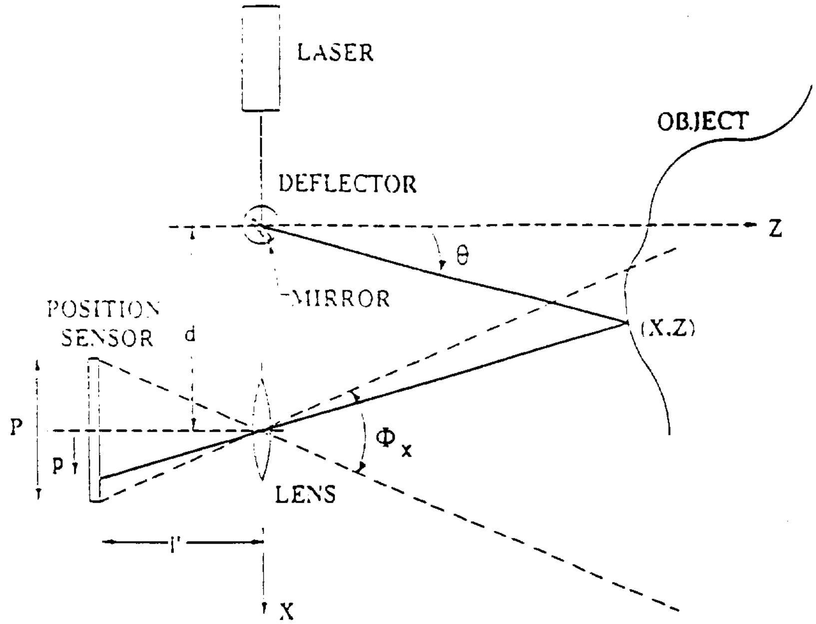


Figure 18. Basic Principle of Optical Triangulation. (after Blais, Rioux, and Beraldin)

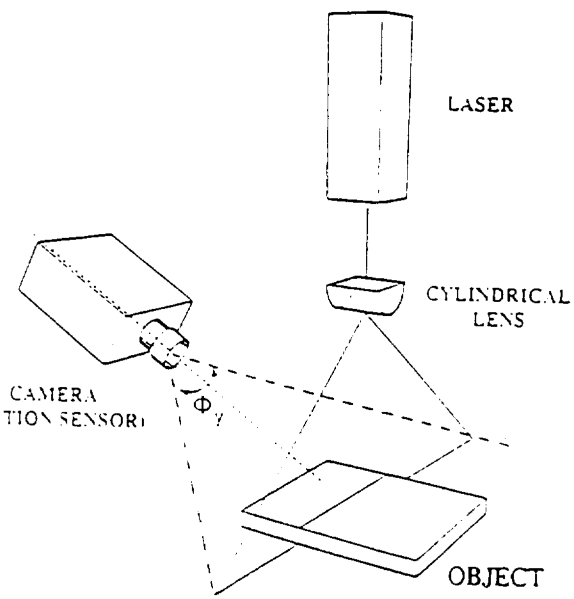


Figure 19. Basic Scheme of Light Sheet Triangulation. (after Blais, Rioux, and Beraldin)

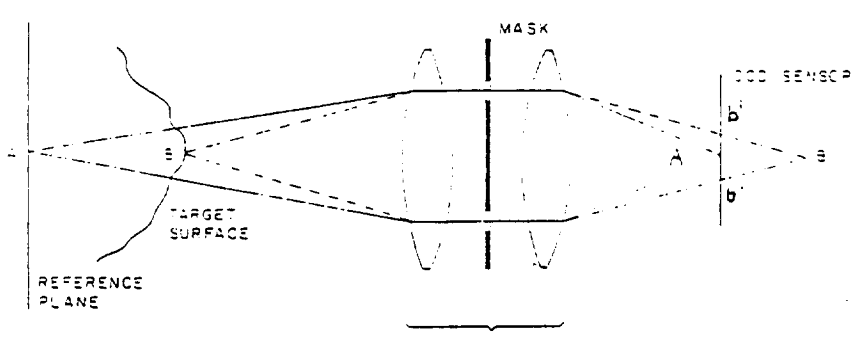
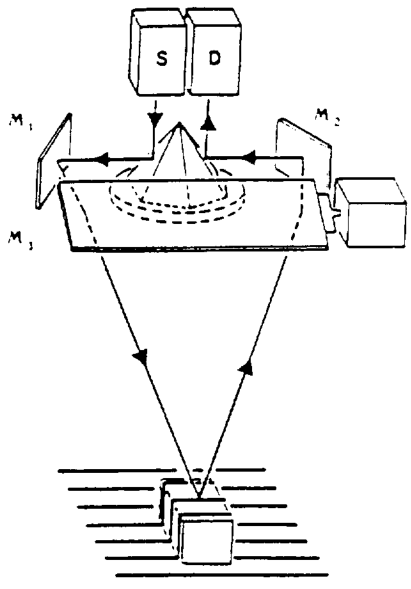


Figure 20. Basic Scheme of Mask Triangulation. (after Blais, Rioux, and Beraldin)



'igure 21. Autosynchronized Geometry with Mirrors (after Rioux)

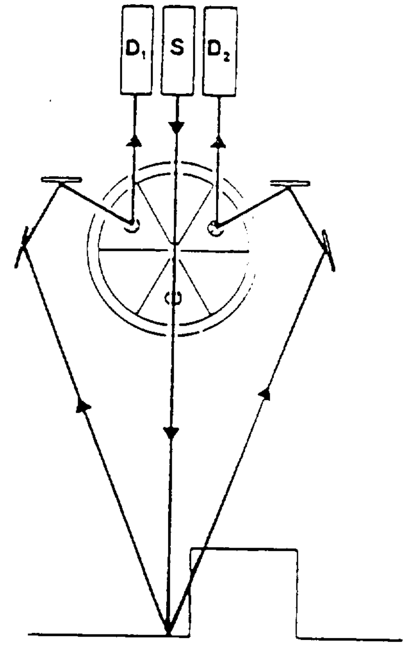


Figure 22. Two Sensors to Minimize Shadows. (after Rioux)

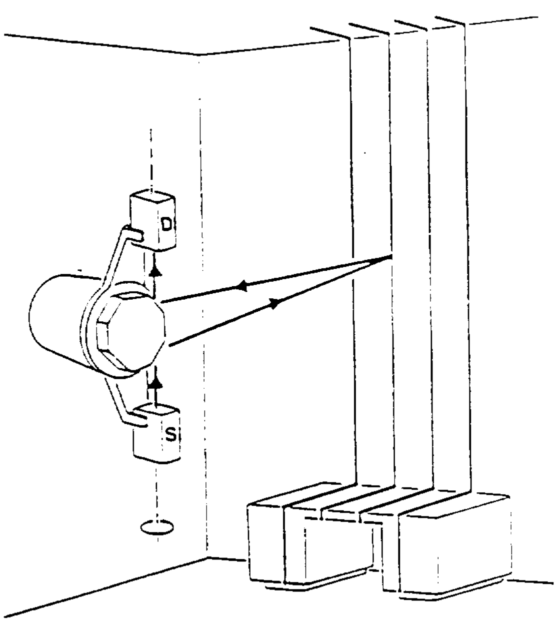


Figure 23. A 360 degree Range Camera. (after Rioux)

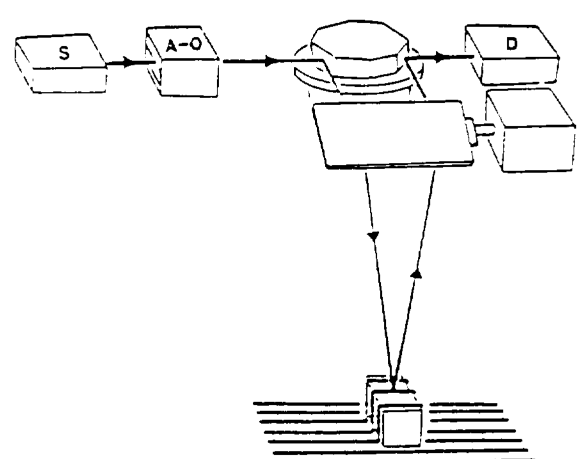


Figure 24. Use of Acoustical Deflector. (after Rioux)

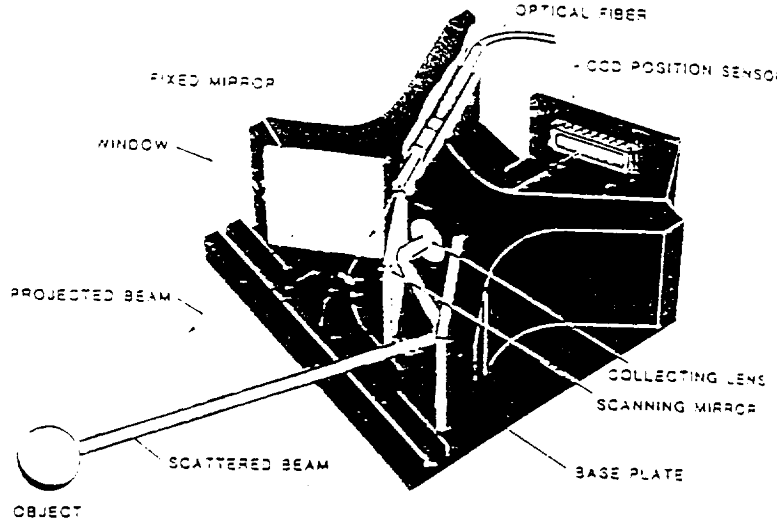


Figure 25. Compact Large Depth of Field Camera.
(after Rioux, Bechthold, Taylor, and Duggan)

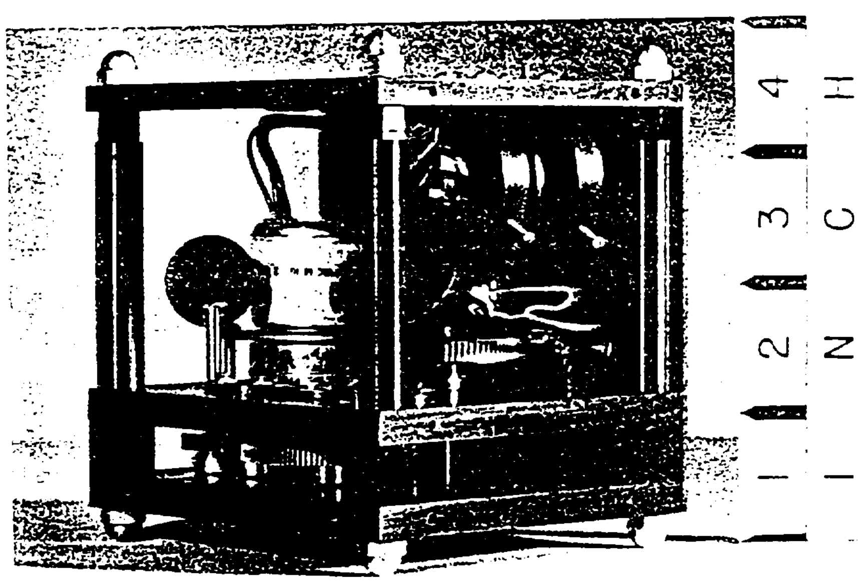
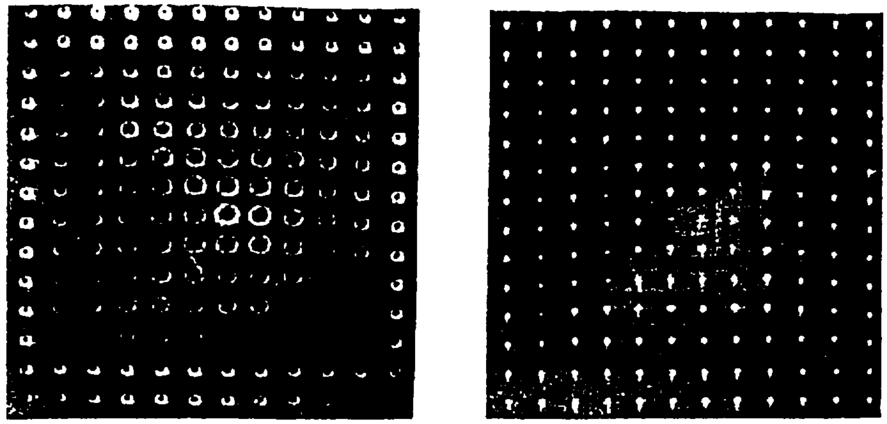


Figure 26. Compact Scanner.
(after Nimrod)



With Mask Without Mask

Figure 27. Example of Structured Lighting with and without Masks. (after Rioux and Blais)

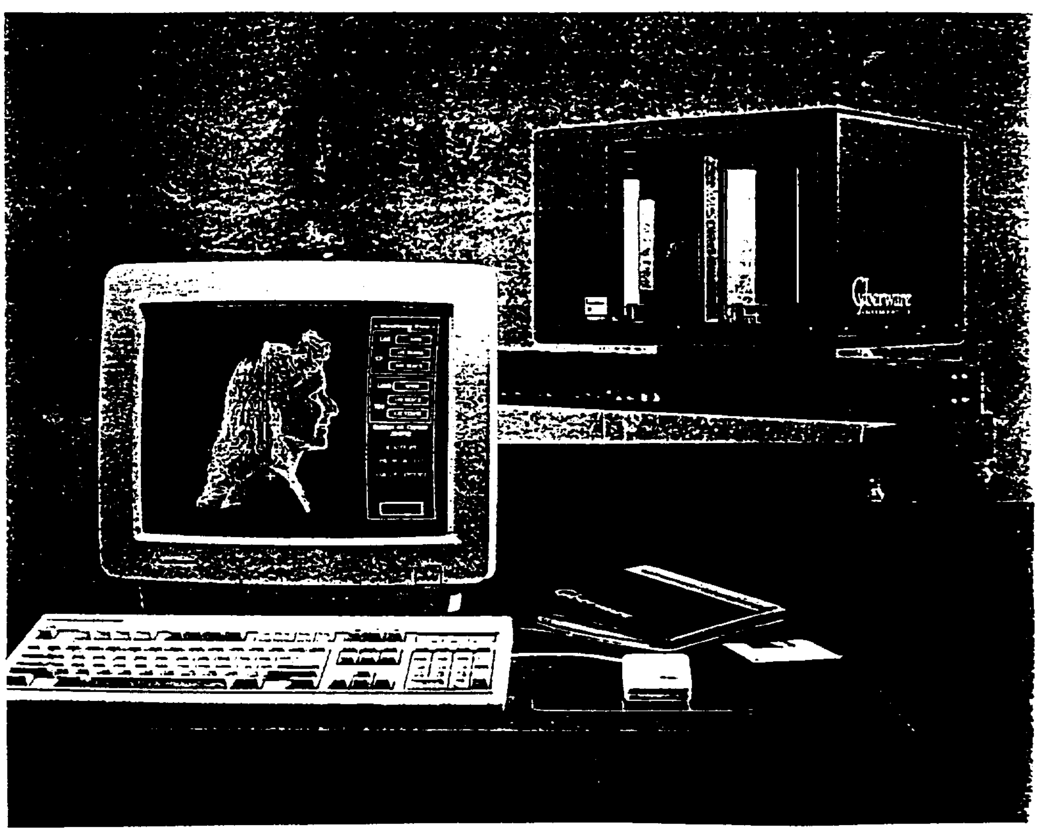


Figure 28. Picture of Cyberware 3-D Digitizer.