ROBOT PERFORMANCE MEASUREMENTS USING AUTOMATIC LASER TECHNIQUES

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ROBOT PERFORMANCE MEASUREMENTS USING AUTOMATIC LASER TRACKING TECHNIQUES

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ABSTRACT

This paper describes two laser tracking techniques currently under development at the National Bureau of Standards for robot performance measurements. Tests indicate that the systems can be used in real-time to determine the three-dimensional static and dynamic positioning accuracy of a robot end effector to a few parts in 100,000 (i.e. 12.5 - 50 um for a medium to large size robot), and wrist orientations to within two seconds of arc. Both systems would be simple and compact enough to be considered as a general-purpose portable calibrating tool for robots (or CNC machines), or as an integral part of a robotic system providing real-time position feedback of the end-effector independent of the position and angle feedback of joint members. The ability to dynamically and statically measure the position of an end-effector to the above accuracy has significant ramifications with regard to meaningful robot performance measurements, and the potential of these systems on other industrial and engineering applications.

1. INTRODUCTION

The position of the end-effector of current robots is determined by computing that position from joint information. This has several serious problems. First, the robot structure must be very rigid because any flexing or bending of the arms causes errors in the robot controller's knowledge of where the end-effector is. The requirement for rigidity increases the cost and weight of the robot, and limits the payload. Second, even with precision encoders and stiff members, the accuracy of large robot is very poor. In a robot with a reach of 2 meters carrying a variety of loads, an absolute accuracy of 1 - 2 mm is typical. This makes most large robots unacceptable for tasks requiring precise knowledge of the position of the end-effector. As the demand for better accuracy performance grows, so as the need for innovative systems and methodologies that can provide accurate information about the position of the robot end-effectors.

The basic problem to be solved is that of locating a point in the three-dimensional space [Ref. 1-6]. Several approaches are being used. They include stereotriangulation with theodolite network and electro-camera system [Ref. 7,8], photogrammetry [Ref. 9], multiple-length measurement with laser interferometry and wires [Ref. 10-11]. These approaches all suffer because 1) they are more complex and costly than are feasible to consider as an integral part of a robotic system, 2) they are too slow to operate in real-time, or 3) they do not provide sufficient accuracy for assembly of tooling and fixturing, inspection, drilling, etc.

This paper details the concept of two automatic single-beam laser tracking interferometer systems (LTIS) under development at the National Bureau of Standards. Preliminary tests indicate that both tracking systems are capable of determining the end-effector position (in either point-to-point or continuous path mode) to about one part in 100,000 (i.e. 12.5 um for a robot with 2 meters of reach), which is about 100 times better than a robot. Techniques of laser tracking using multiple-beams are also discussed.

2. 5-DIMENSIONAL LASER TRACKING INTERFEROMETER SYSTEM (5-D LTIS)

2.1. Concept of the 5-D LTIS

The automatic 5-dimensional laser tracking interferometer system (5-D LTIS) is a dynamic tracking system designed to measure the position of a moving target in five axes; namely, X, Y, Z plus pitch and roll. Figure 1 illustrates a 5-D LTIS which comprises of three major components: a micro-computer, a portable tracking unit and a target unit. The tracking unit, including a laser interferometer system, a dual-axes servo-controlled tracking mirror and a tripod, is firmly located at some convenient position away from the robot. The target unit consists of a dual-axes servo-controlled partial mirror (15% transmission) and two bi-lateral-effect photodiodes (installed at back of the mirror) is mounted on the robot wrist. The control objective of the laser tracking system is to accurately servo the angles of the tracking mirror and direct the laser beam to the center of the target mirror. In the meantime, the target mirror is also servoed to stay perpendicular to the in-coming beam and return the beam precisely back to the source. The laser system, therefore, measures the change in radial displacement between the target mirror and the tracking mirror. An initial absolute distance calibration process is required in order to obtain the absolute position of the target from the tracking mirror. The two photodiodes at back of the target mirror are used to supply information about the beam position on the photodiodes to the micro-computer through four A/D converters to close the servo-loop.

The measuring origin of the system is point A, which is defined by the intersection of the vertical (Theta A) and horizontal (Phi A) axes of the tracking mirror. Similarly, the measuring point is B, which is defined by the intersection of the vertical (Theta B) and horizontal (Phi B) axes of the target mirror. Each rotating axis is coupled with a high precision encoder. Hence, by incorporating the angle outputs of Theta A and Phi A and the absolute distance between point A and B, the X, Y and Z positions of the target mirror, and thus the position of the robot end-effector, can be computed in spherical coordinates. Since the target mirror is controlled to stay perpendicular to the in-coming beam during the tracking process, the pitch and roll orientations of the target mirror relative to the measuring origin can be readily related to the measurements of Theta B and Phi B angles.

2.2. Theory of Operation of the 5-D LTIS

A dual-frequencies Zeeman-Split Plane Mirror Interferometer Laser System is chosen for the 5-D LTIS. A similar system had been successfully applied to an earlier experimental 2-D LTIS, and had established some fundamental knowledge for the 5-D system. Figure 2 shows the schematic of the plane mirror interferometer used in the 2-D LTIS. Two orthogonally polarized beams (referred as the reference and measuring beams) at narrowly-spaced frequencies are provided by the laser. The reference beam enters the interferometer, is immediately reflected at the polarizing beamsplitter and returned to the fringe counter. The measuring beam proceeds through the interferometer and is circularly polarized after passing through the quarter-wave retardation plate. 20% of the intensity is then transmitted through the target mirror and reached to the first bi-lateral-effect photodiode DA while the rest is reflected off the target mirror and returned to the interferometer. As the beam passes through the retardation plate the second time, its polarization is further rotated by 45 degrees and is, therefore, linear and having the same polarization as the reference beam. It is then reflected upward in the beamsplitter to the upper retroreflector, offset and reflected downward, and exit the beamsplitter to form a second beam path. After passing the retardation plate the third time, the beam is returned to the retardation plate again by the target mirror while allowing another 20% of the intensity to reach diode DB. As the beam passes through the plate the fourth time, the polarization has already been rotated for a total of 360 degrees (resumes its initial polarization state). It then passes through the interferometer and emerges into the fringe counter where it is optically combined with the reference beam.

The output of DA is a d.c. voltage proportional to the position of the first beam on DA in the X-axis. The signal is fed to the computer through a A/D converter to determine the amount of position offset between the desired and actual position of the beam, and to compute the appropriate "error-correcting" command for the Theta A axis of the 2-D tracking unit. The output of DB represents the position of the second beam on DB. Its magnitude is dependent on the non-squareness between the measuring beam and the surface of the target mirror in the X-Y plane, and the distance AB. Similarly, the signal from DB is fed to the computer through another A/D converter to compute the "angular error-correcting" command for the Phi B axis of the target mirror.

Instead of servoing the entire tracking unit as in the 2-D system, the 5-D system utilizes a servoed tracking mirror to actively direct the beam to the target (Fig. 1). This arrangement introduces a new problem-- as the tracking mirror rotates around the vertical axis, the first and second beams will rotate relative to each other along the measuring axis. To eliminate this problem, the original 2-D configuration is modified to adopt a so-called "pseudo-single-beam plane mirror interferometer." This modification involves merging the two beams together by centering the beam with the interferometer (Fig. 3), and by employing an additional quarter-wave retardation plate and a polarizing beamsplitter to separate the beams beyond the target mirror for control purposes.

The 5-D LTIS operating theory is essentially similar to the 2-D's described above. In the 5-D system, both DA and DB are respectively used to supply two-dimensional feedback information to the computer for the control of the tracking and target mirrors. As the target mirror is driven in either the Y- or Z-axis, a two-dimensional offset signal (error) indicating a change in the original beam position is immediately detected and generated by DA and fed to the control computer through two A/D converters. The information is promptly processed by the computer to yield the appropriate commands for the Theta A and Phi A axes of the tracking mirror to null the offset. While the tracking mirror is rotated in an effort to null DA's output, an angle misalignment between the target mirror and the measuring beam is created and detected by DB. A two-dimensional signal proportional to the amount of misalignment is output by DB and fed to the computer. The information is processed to generate the appropriate commands for the Theta B and Phi B axes of the target mirror to null DB's output. For a pure translation of the target mirror along the measuring axis, no change of lateral displacement is observed by either photodiode. Consequently, the control action is minimum and the tracking system merely updates the change of radial distance of the target from the measuring origin.

The laser tracking system is conceptually nearly identical to a so-called "Total Station" widely used in field surveying. Major error sources like angular encoding errors, height of standards errors, distance measuring errors, collimation errors, etc., found in the tracking system can be analysed using similar techniques as described in Ref. 12, 13. A brief error analysis of the 5-D LTIS can be found in Ref. 14. Based on these analyses, a projected measuring accuracy of about two parts in 100,000 (i.e. +/- 40 um in a 2x2x2 cubic meter measuring volume) and pitch and yaw angles to better than one arc-second can be achieved by the 5-D system.

2.3. Experimental Results of the 5-D LTIS

In order to demonstrate the tracking feasibility of the "pseudo-single-beam plane mirror interferometer", an experimental 5-D LTIS without angular encoders was built and tested. Figure 4 illustrates the experimental setup which utilized a manual driven coordinate measuring machine (CMM) as a test bed. The tracking unit (Figure 5) including a Hewlett Packer 5501A* plane mirror interferometer system [Ref. 15] and a tracking mirror was firmly located at a distance of two meters away from the CMM having a work volume of 1.5x1.5x1.5 cubic meters. The target mirror was rigidly mounted on the ram of the CMM and weighs about one kilogram. The window of the target mirror is 13 millimeter in diameter while the size of the laser beam is approximately 8 millimeter in diameter. Thus the effective servo-range for tracking control is +/- 2.5 millimeter. Figure 6 shows the schematic of the gimbel design for both the target and tracking mirrors. Two Inland Company* d.c. motors [Ref. 16] are installed on the gimbel device: a QT-0706 (11.6 N-cm.) motor and a QT-1207 (19 N-cm.) motor for the horizontal and vertical axes respectively. Both axes use an Inland Company TG-1203 tachometer to provide velocity feedback to the computer. Figure 7 and 8 are, respectively, pictures of the dual-axes tracking and target mirrors constructed according to the design shown in Figure 6.

The feasibility of the 5-D LTIS was demonstrated as the laser beam was successfully controlled to lock-onto the center of the target mirror while it was randomly driven within the work volume of the CMM at maximum speed (10 cm/sec.). Based on the voltage readouts of DB (representing the angular misalignments) and the tracking distance of 2 meters (the effective tracking distance is twice of that amount since the measuring beam travels between the target and tracking mirrors twice), the angular control accuracy of all four axes are found to be on the order of 0.5 arc-second. The change of radial distance obtained from the laser system was compared with the readouts of the CMM to yield the repeatability of the tracking system (total measuring accuracy could not be obtained since angular encoders were not used in the experimental setup). Tests indicate that the 5-D laser tracking system has a repeatability comparable to that of the CMM, which is in the order of +/-10 micrometer. This implies that the repeatability of the laser system could be better than +/- 10 micrometer over a 1.5x1.5x1.5 cubic meter volume. Based on these results and the error analysis, it is conceivable that, with good manufacturing practise and angular encoder (e.g. one arc-second accuracy), an overall measuring accuracy of two parts in 100,000 or better can be achieved by such a system.

3. 3-D LASER TRACKING INTERFEROMETER SYSTEM (3-D LTIS)

3.1. Concept of the 3-D LTIS

The 5-D LTIS has been basically proven as an advanced, flexible and accurate multi-degree-of-freedom measuring system which has the potential of offering a variety of application opportunities. However, it is also recognized that there are applications where measurements of the X, Y and Z positions of the target are considered adequate. In these cases the 3-D LTIS, which employs a passive target (i.e. a "cat's eye" or a "corner reflector", generally referred as a retroreflector in this text) instead of a servoed target, becomes more economical and practical. The property of a retroreflector is that for a collimated beam striking the retroreflector off-center (Fig. 9), it will emerge parallel to the in-coming beam with twice the amount of lateral offset. Thus for a beam striking the center of the precision retroreflector, it will be returned to the source literally on the same path.

3.2. Theory of Operation of the 3-D LTIS

Unlike the 5-D system which utilizes a "pseudo-single-beam plane mirror interferometer" for distance measurements, the 3-D system shown in Fig. 10 employs a "dual-frequencies single-beam interferometer." Two orthogonally polarized beams (referred as the reference and measuring beams) at narrowly-spaced frequencies are provided by the laser. The reference beam is immediately reflected off the polarizing beamsplitter of the interferometer and returned to the fringe counter. The measuring beam passes through the interferometer and a 50% beamsplitter where half of its intensity is lost. It is then directed to the center of the passive target (i.e. retroreflector) through a dual-axes servoed tracking mirror. The beam is then returned (without offset) to the tracking mirror and the interferometer, and enters into the fringe counter where it is optically combined with the reference beam. On its return path to the fringe counter half of its intensity (25% of the original) is deflected by the beamsplitter and reached to the bi-lateral-effect photodiode DA. The magnitude of the bi-lateral offset of the beam from the centroid of DA is indicated by the X and Y voltage outputs of DA. The information is fed to the micro-computer which determines and issues the appropriate servo-commands to the tracking mirror to null the DA outputs.

Prior to the tracking process, the outputs of DA are nulled by aligning the measuring beam with the optical center of the retroreflector. The residual outputs are registered into the computer through two A/D converters as the control references. As soon as the target is driven to move (i.e. sideway) a lateral offset between the in-coming and the returning beam is immediately introduced and sensed by the photodiode. The information is promptly fed to the computer for processing. The computer then determines and issues the appropriate "error-correcting" servo-commands for the Theta A and Phi A axes of the tracking mirror. On the other hand, if the target mirror is to move along the measuring axis of the beam, no offset is observed by DA and no control action will be implemented. However, the laser system will continue to update the change in radial displacement of the target.

3.3. Experimental Results of the 3-D LTIS

An experimental 3-D LTIS shown in Fig. 11 was built and tested using similar setup and equipment as in the 5-D experiment. The tracking unit was, again, located two meters away from the CMM. A 25 millimeter diameter "hollow" retroreflector weighing less than 0.1 kilogram with one arc-second accuracy was mounted onto the ram of the CMM, replacing the need of a servoed target as in the 5-D system. During the tracking process, the target (retroreflector) was randomly moved throughout the work volume of the CMM at maximum speed (10 centimeter/second). The laser beam maintained lock-onto the center of the target. No significant reduction of beam intensity or loss of fringe countings were evident. As with the previous experiment, the system measuring accuracy was not accessible because angular encoders were not used. However, based on similar repeatability and control accuracy analyses, the test results are essentially the same. That is, a repeatability of +/- 10 micrometer (comparable to that of the CMM) and an angle control accuracy of +/- 0.5 arc-second over a 1.5x1.5x2 cubic meter volume. Based on these results, a projected accuracy of two part in 100,000 is considered achievable.

4. MULTI-STATIONS LASER TRACKING SYSTEMS

4.1. Two-Stations 3-D Laser Tracking System

Another possibility of achieving 3-D measurements based on the laser tracking concept is the use of a Two-Stations Tracking System shown in Fig. 12. Two independently servoed dual-axes tracking stations are employed to track the motion of a common passive target (i.e. a retroreflector). The tracking operation of each station is similar to the 3-D's discussed above except that the distance measurements in the two-station system are not obtained by interferometry technique, but by triangulation (based on the knowledge of the distance between the two stations M1M2 and any three of the four angle readouts, Theta A, Phi A, Theta B and Phi B). Two major advantages of the two-stations system over the 3-D LTIS are that it is an absolute measuring system and is therefore more impervious to lost of the absolute distance measurement due to momentarily blockage of the beam path. Secondly, it eliminates the need of an expensive laser interferometer system.

One of the disadvantages in the two-stations system is that the measuring accuracy of the system is largely dependent on the dimensional stability of the three spatial distances M1M2, M1B and M2B, and the accuracy of the distance calibration between the two stations. Enviromental factors such as change of reflective index of air, thermal gradients and vibration of the base stations are some of the sources for the dimensional instability. The 3-D and 5-D single-beam systems involve one spatial measurement and one single station and are, therefore, less subjected to enviromental effects. Furthermore, the 3-D or 5-D system is more compact and portable to be considered as a general metrology system for a variety of applications.

4.2. Three-Stations 3-D Laser Tracking System

The idea of using multi-stations tracking system can be easily expanded to include the three-stations laser tracking system. Somewhat similar to the operation of the single-beam 3-D LTIS, a three-stations system employes three independent single-beam tracking units to track one common passive target (Fig. 13). Each tracking unit incorporates its own laser interferometer measuring system and a dual-axes tracking mirror. Position measurements of the target are computed based on the knowledge of the three "length" measurements A1B, A2B and A3B, and the precalibrated base distances between each station A1A2, A2A3, and A3A1. However, this system presents little or no significant advantages over the other systems mentioned above.

5. CONCLUSIONS

The potential measuring accuracy of the LTISs is generally ten to a hundred times better than most of the robots built today. One of the tasks which will need to be addressed is how to best exploit this accuracy. For inspection, the robot could pick up a touch probe with the target reflector assembly mounted onto the probe. The tracking system will continuously compute the coordinates and orientations of the probe origin. For assembly, this system can provide on-line position feedback control of the robot end-effector independent of the feedback from joint members. And for robot accuracy enhancement, the system can be used to generate a static or dynmaic error map of the robot which can be used later by the robot controller to compensate for the error.

In areas such as robot performance measurements and standardizations, the laser tracking system can offer the speed, accuracy, flexible and range that no single system currently can. At this stage, a full 5-D LTIS is under construction at the National Bureau of Standards. The designed accuracy is two parts per 100,000 with a measuring volume of approximately 3X3X3 cubic meters and a maximum tracking speed of 300 mm/sec. It is expected to be completed by June, 1986 and will serve as a general calibration tool for robot performance measurements.

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* "Certain commercial equipment, instruments or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose." (NBS Communications Manual for Scientific, Technical and Public Information, Nov. 1980, pp. 9 & 10).

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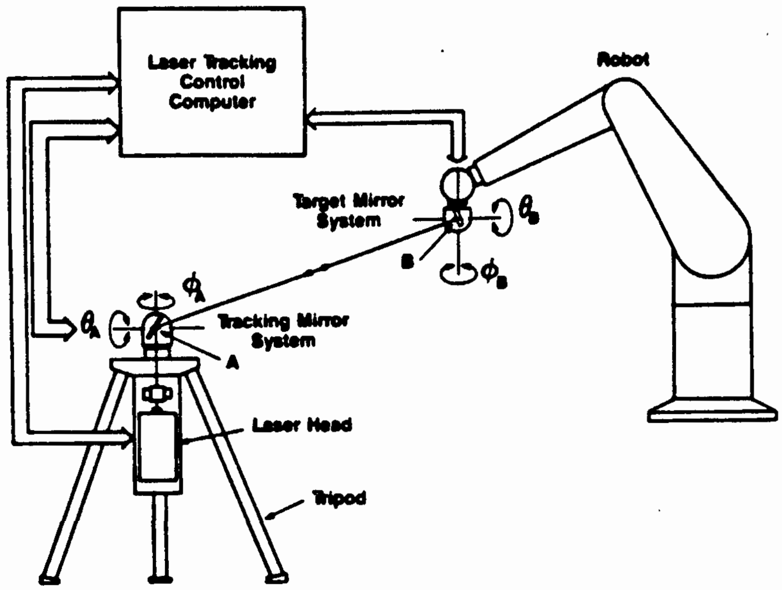


Figure 1. 5-D Laser Tracking Interferometer System (5-D LTIS)

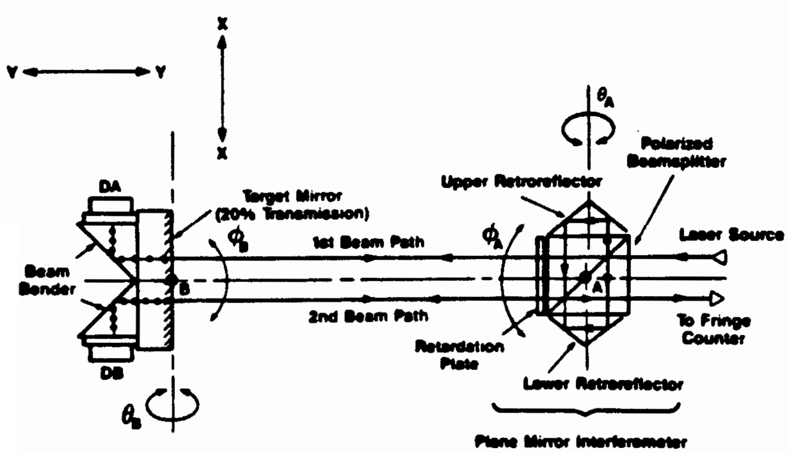


Figure 2. Plane-Mirror-Interferometer Setup for 2-D LTIS

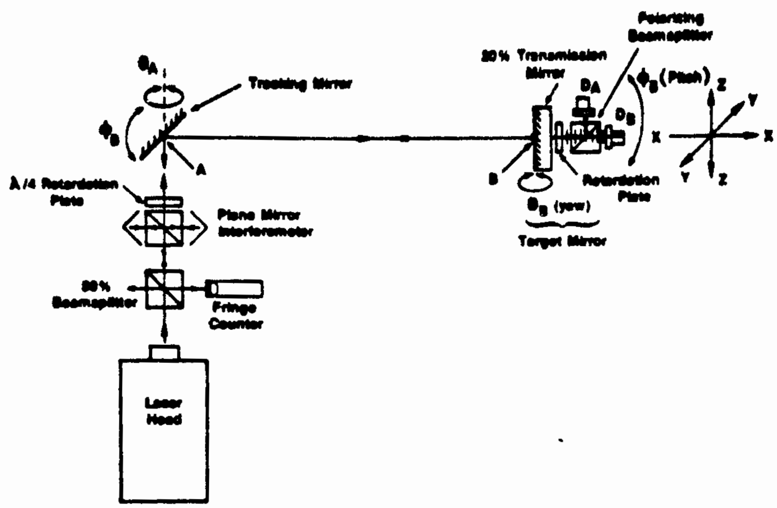


Figure 3. Pseudo-Single-Beam-Interferometer Setup for 5-D LTIS

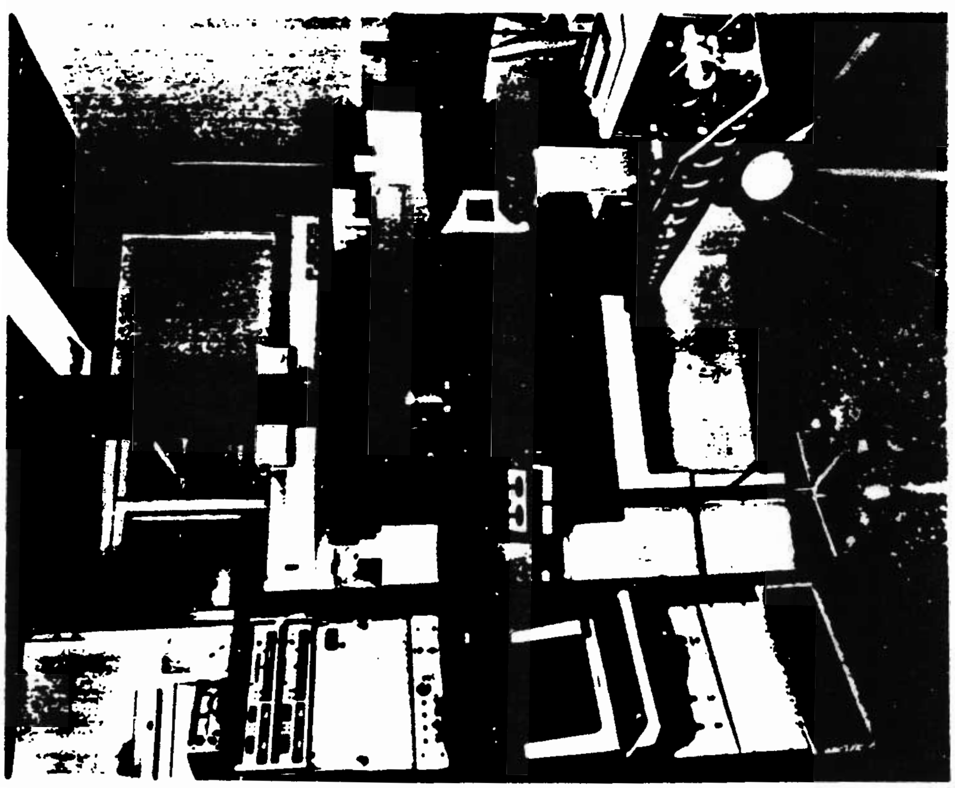


Figure 4. Experimental 5-D LTIS Setup

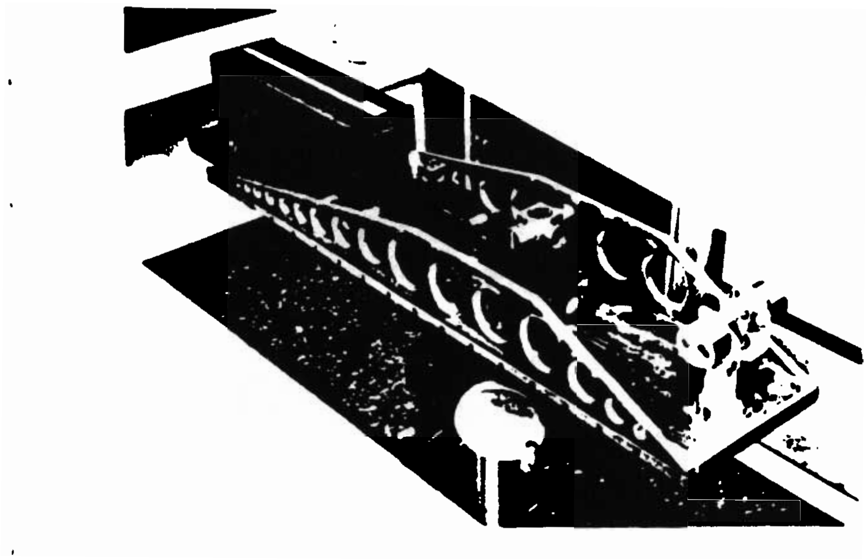


Figure 5. 5-D LTIS Tracking Unit

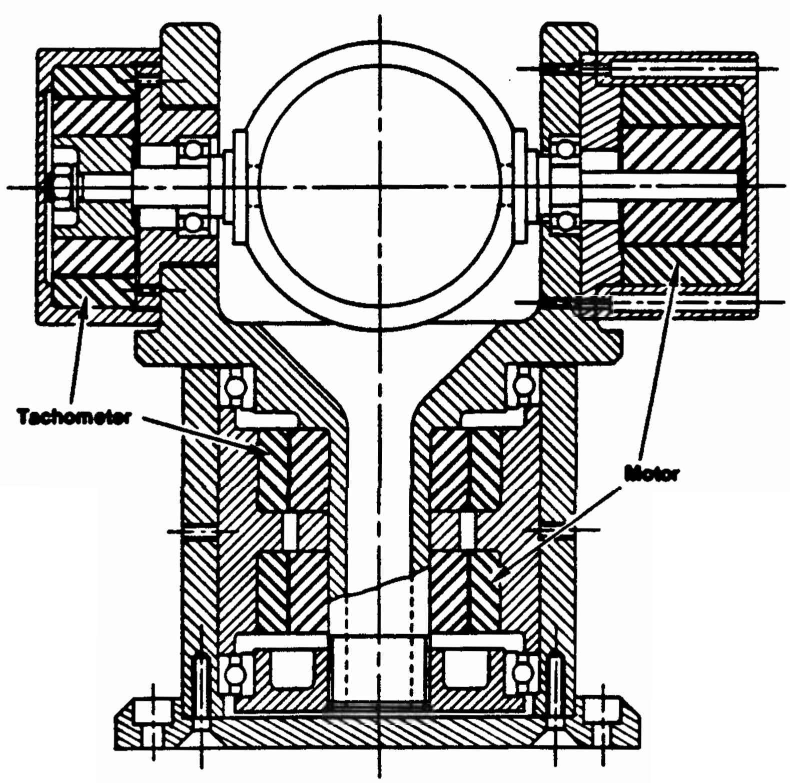


Figure 6. Dual-Axes Gimbel Design

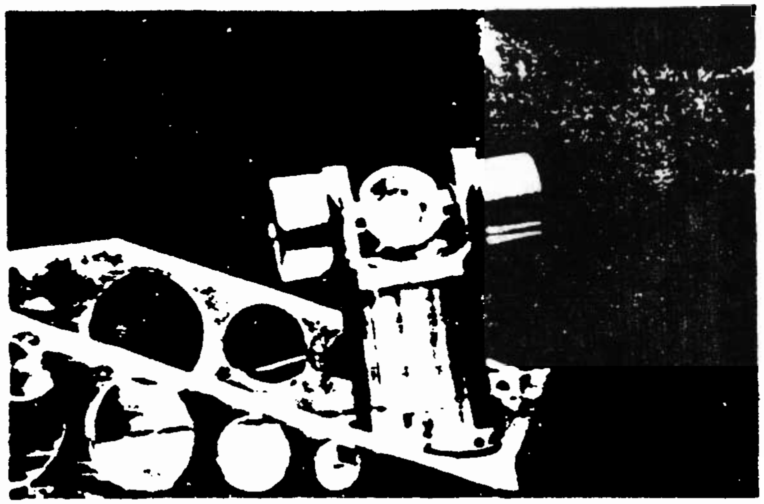


Figure 7. Dual-Axes Tracking Mirror

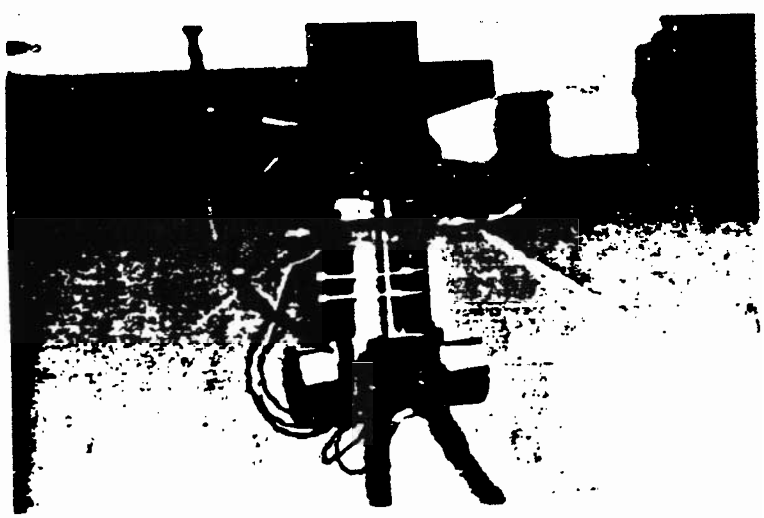
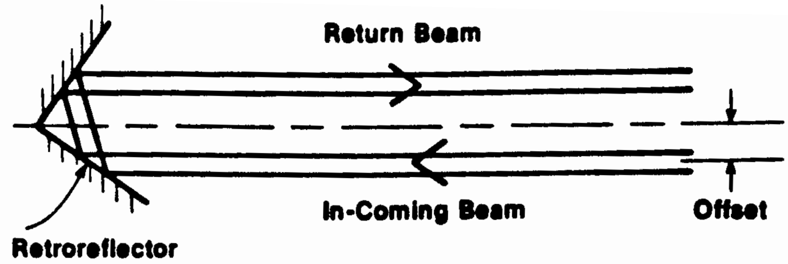
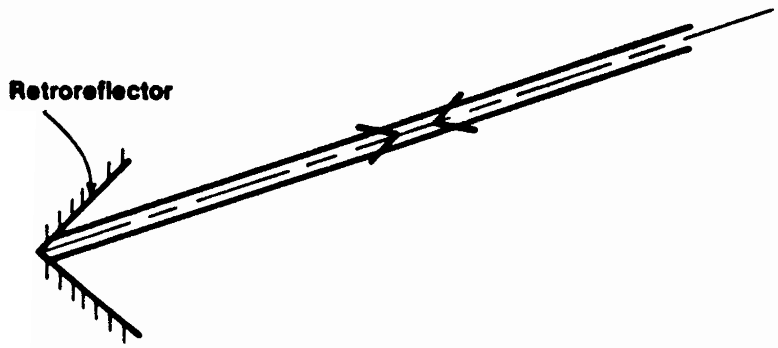


Figure 8. Dual-Axes Target Mirror



Beam Striking the Retroreflector Off-Center



Beam Striking the Retroreflector at Center

Figure 9. Properties of a Retroreflector

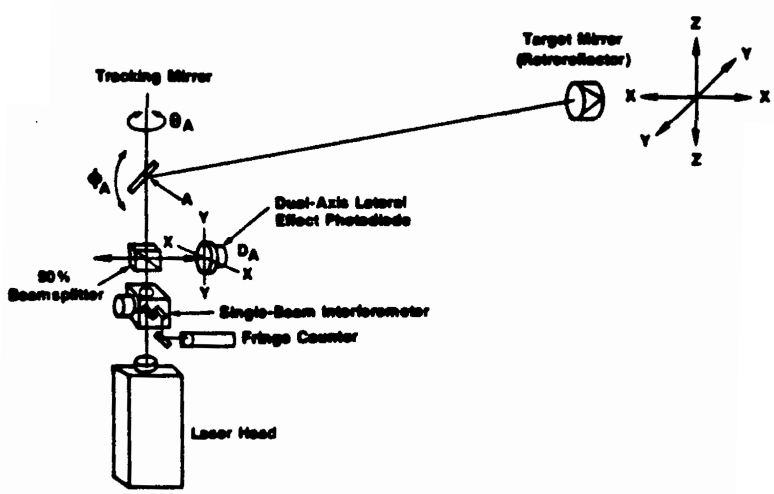


Figure 10. Configuration of a 3-D LTIS

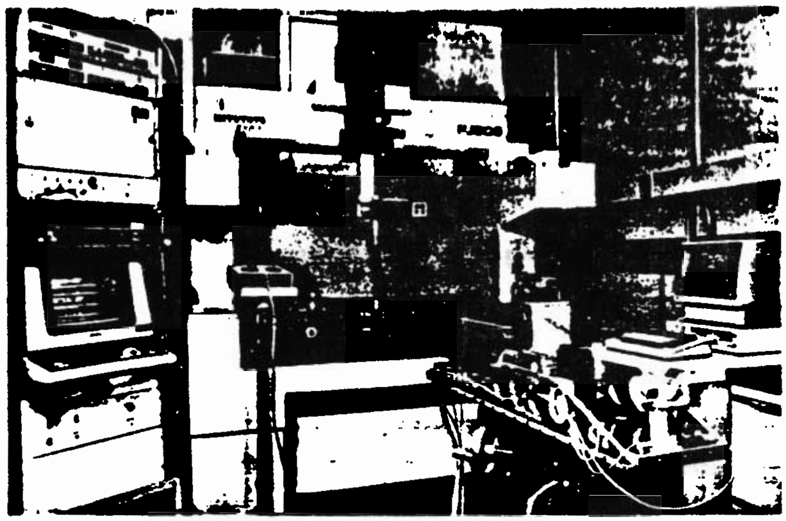


Figure 11. Experimental 3-D LTIS Setup

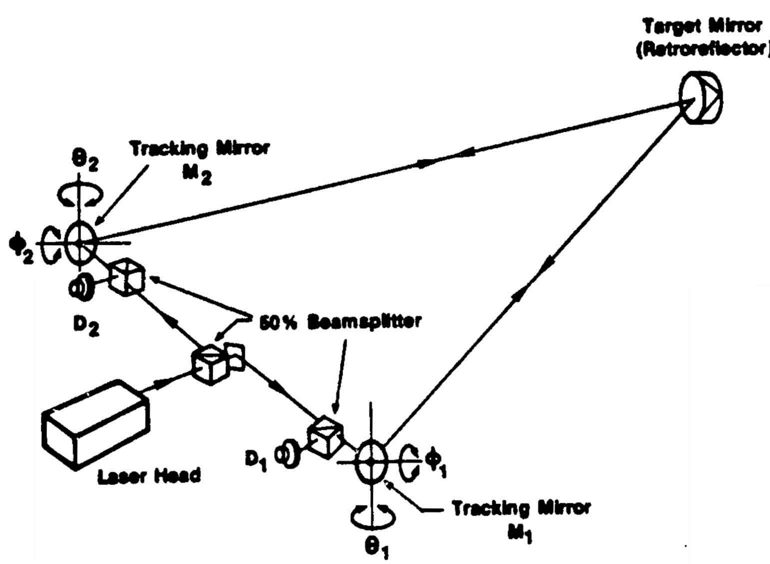


Figure 12. Two-Stations 3-D LTIS

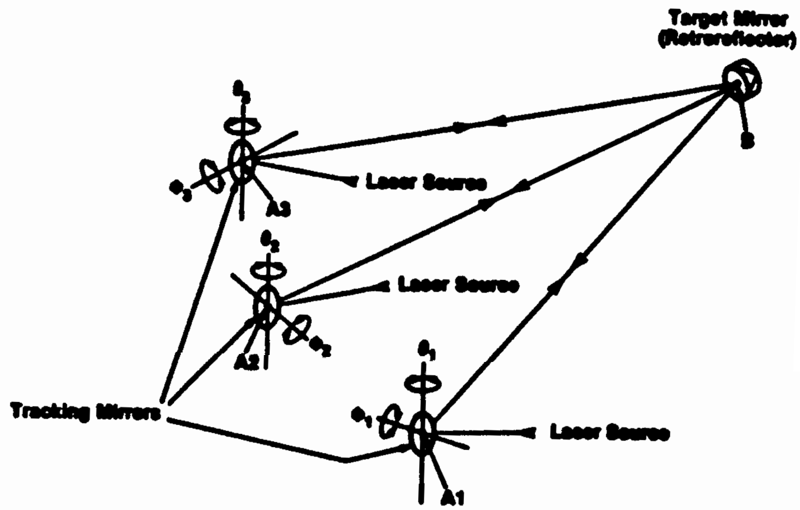


Figure 13. Three-Stations 3-D LTIS