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**VERTICAL SCANNING LONG TRACE PROFILER:
A TOOL FOR METROLOGY OF X-RAY MIRRORS***

**Haizhang Li
Continental Optical Corporation
Hauppauge, NY 11788**

**Peter Z. Takacs
Brookhaven National Laboratory
Upton, NY 11973-5000**

**Tom Oversluizen
Creative Instrumentation
East Patchogue, NY 11772**

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Haizhang Li, member SPIE
Continental Optical Corporation, Hauppauge, NY 11788

Peter Z. Takacs, member SPIE
Brookhaven National Laboratory, Upton, NY 11973

Tom Oversluizen
Creative Instrumentation, E. Patchogue, NY 11772

ABSTRACT

This paper describes the development of a prototype instrument of the Vertical Scanning Long Trace Profiler (VSLTP) under a SBIR Phase II grant from NASA. The instrument is capable of scanning shell mirrors with a diameter as small as 100mm for a travel distance of 700mm in vertical configuration. Main components of the optical system are described. It has a beam separation set, a beam splitting set, a Fourier transform lens system, a penta prism pair, a Risley prism pair and a cylinder lens. The main hardware and software for implementation of the prototype instrument are also presented. They include the major mechanical structure, 9-axis motion control system and the data acquisition and analysis software. The design of the optical and mechanical systems makes the VSLTP very tolerable to the deformation of the slide deformation, laser pattern shift and fluctuation due to temperature change. Results obtained from the Phase I show that the VSLTP instrument is capable of a measurement accuracy of 50 nm for the height and 1 microradian for the slope.

Keywords: Interferometry, Metrology, X-ray Optics, Synchrotron radiation Optics, Laser scanning device

INTRODUCTION

X-ray telescope optics, such as the Advanced X-ray Astrophysics Facility (AXAF) [1,2], are often made of a series of nested shells, each of them is in the shape of a pair of paraboloids and hyperboloids with long axial radii of curvature (typically hundreds of meters) and short sagittal radii (from 10 to 100 cm), as shown in Figure 1. They are nearly impossible to be tested by conventional interferometric techniques. In addition, the thin shells are very susceptible to self-weight deflection caused by gravity and should be tested in a vertical configuration. The metrology requirements for these mirrors are extremely challenging. In early 1995, under a SBIR Phase I research grant from NASA, we developed an experimental VSLTP which is capable of measuring the surface figure of x-ray telescope mirrors in a vertical orientation[3]. Initial experimental results from measurements of an x-ray telescope mandrel show that the prototype instrument is capable of achieving a height measurement accuracy of about 50 nanometers with a repeatability of better than 20 nanometers, and a slope measurement accuracy of about 1 microradian. Since 1996, we have started building a prototype VSLTP under a SBIR Phase II grant from NASA. The main efforts in phase II are in design, manufacturing, and assembly of the optical, mechanical and electronic parts, development of the computer software for data acquisition, implementing algorithm for 3D reconstruction of the mirror surface. The instrument can scan the X-ray telescope shell mirrors with a diameter as small as 100mm, traveling 700 mm vertically, 900 mm horizontally, and 360 degrees rotationally. The

VSLTP measures the slope of the mirror surface by detecting the phase difference between two separated laser beams. By integrating the slope data, one can obtain the height profiles.

DESCRIPTION OF OPTICAL SYSTEM

Figure 2 shows a schematic view of the prototype VSLTP optical system. The components inside the dashed line are the same as in a standard Long Trace Profiler (LTP II) optical system [4, 5]. A single mode polarized beam from a HeNe laser is launched into a polarization-preserving fiber. Both ends of the fiber are collimated. The beam then goes through an attenuator (composed of two fixed polarizers and one rotational polarizer) and enters the non-polarizing cube beamsplitter. The single beam is split into two equal components, which then go through two separate Porro prisms and then return back into the cube beamsplitter. One of the Porro prisms can be adjusted in the transverse direction, which provides lateral displacement between the two beams while maintaining their exact colinearity. After exiting the first beamsplitter, the probe beam pair goes first through a half-wave rotation plate, and then through a polarizing beamsplitter cube. This cube splits the beam pair again into two sets, one set exits the cube vertically and is directed toward a flat reference mirror, the other exits horizontally to hit the surface under test. These beams are nominally circularly polarized after exiting the polarizing cube which has 1/4 wave plates attached to the exit faces. The intensity between the two beams is adjusted by rotating the half-wave plate to obtain equal intensity in the test and reference fringe patterns. The relative intensity between the two beams needs to be adjusted depending on the reflectivity of the surface under test. Both probe beam pairs return upon reflection to pass back through the polarizing cube, and are then brought to separate focal points on the detector, via a Fourier transform lens. Within each focal spot, a fringe pattern is formed. The pattern is formed from the interference fringes between two components of the beam pair modulated by the laser aperture function. By measuring the minima of the pattern, one could detect the relative phase change of the two probe beams thus obtain the surface slope information. The interference patterns are recorded by a 2x1024 linear dual array photo-diode detector. The direction of the linear photo-diode array is parallel to that of the beam separation. The focal length of the Fourier lens is more than 1 meter and the dimension of the photo-detector array is about 1 inch. For most mirror surfaces with a radius of curvature larger than 10 meters, this system can achieve an accuracy of 1/10 wave length for the height profiles and better than 1 micro-radius rms for the slope profiles. However, the standard LTP II can only measure the mirror surface in a horizontal direction. It is a 1D measuring instrument and has been used in scanning along the symmetry line of cylindrical SR mirrors for many years.

For AXAF applications, the shell mirrors have to be tested in a vertical configuration. Further more, a 3D mapping of the surface is desired. To meet these requirements, we did a number of modifications and additions to the standard LTP II system. The major components added are: a Dove prism, a pair of penta prisms, a pair of the Risley prisms and a cylinder lens. They are shown in the left side of Figure 2.

The Dove prism is rotated around its optical axis by 45 degrees, thus rotating the direction of the beam separation by 90 degrees. During the vertical scan, the Dove prism is out of the optical path. In this case, the direction of the beam separation is parallel to the paper plane and the profiles in meridional direction can be obtained. To obtain profiles in the azimuthal direction, the Dove prism should be inserted into the optical path. It produces the required 90 degree beam rotation. The direction of the beam separation after exiting the Dove prism becomes perpendicular to the paper plane so that the slope profiles in the azimuthal direction could be detected. Upon reflecting from the test surface and through the Dove prism, the beam pair undergoes an additional 90 degree rotation for a total rotation of 180 degrees. The interference fringes on the detector are again oriented in the proper direction.

The main function of the penta prism pair is to provide vertical scanning ability. Using the penta prism in a pencil beam interferometer was originally proposed by von Bieren[6]. S. Qian [7] reported experimental results with Penta Prism Long Trace Profiler (PPLTP). The VSLTP uses a pair of penta prisms with one of them fixed onto the vertical frame and another moving with the vertical arm. The beam exiting from the moving penta prism is perpendicular to the rotational axis of the shell mirrors. However, the segments of shell mirrors are usually conical shapes. A pair of adjustable Risley prisms was added after the moving penta prism to permit the beam to be directed toward the normal to the tilted surface. The returning beam thus remains in the scope of the detector. The Risley prism pair also provides an offset between scanning the paraboloid and hyperboloid portions of the mirrors. To compensate the focusing effect caused by the short sagittal radii of the shell or mandrel mirrors, a cylinder lens is used in front of the Risley prisms. For measuring the shell mirror, the cylinder lens should have a negative focal length and the absolute value of the cylinder focal length should be smaller than the radius of the shell mirror. The back focal point of the negative cylinder lens should be coincident with the axis of the shell mirror.

PROTOTYPE INSTRUMENT

In the Phase I research period, we built an proof-of-principle experimental setup based on the above optical system. The main tasks in the Phase II research period are to design, build and deliver a prototype VSLTP instrument that is capable of measuring x-ray mandrels and shell mirrors in a vertical configuration with the accuracy achieved in Phase I. Much progress has been made in design of the mechanical and electronic parts and the computer software. Figure 3 shows major sub-systems in the VSLTP prototype instrument. They are: optical board and its support, vertical arm, vertical slide, horizontal slide, slide support, kinematic mounts, legs, and rotary table. The dimensions of the instrument are about 2.5m x 2.5m x 1m as shown in the Figure.

The vertical slide sub-system is composed of a frame and a DAEDAL motorized ball bearing linear table with a travel distance of 750mm. The horizontal slide sub-system is a Thomson SmartRail double shaft ball bearing slide with a travel distance of 900mm. The vertical slide is mounted on the top of the horizontal slide which sits on the slide support formed by four 3"X3" hollow steel tubes. The kinematic mount is basically a structure similar to the cone, groove and flat mechanism that has been successfully used in Synchrotron beam line experiments for years[8]. The rotary table, made by DOVER instrument, has an air bearing system, capable of rotating 360 degrees with 400 lb. load capacity. The tilt/centering table above the rotary table is used for the alignment of the mirrors under test. The support of the optical head, legs and the rotary table are fixed on to an optical breadboard isolated from vibration.

The optical components drawn inside the dashed line in Figure 2 are mounted on the optics board, with the exception of the HeNe laser head and the reference mirror, which are separated from the optics board. The laser head is mounted where the heat generated during its operation will not affect the rest of the system. The reference mirror, however, should be fixed either onto the top surface of the optical breadboard or to the stationary part of the rotary table. Introducing the reference mirror is the key step to compensate the effect of the pattern shift caused by temperature. Of the components outside of the dashed lines in Figure 2, only the Dove prism is mounted on the optical board. A micro stepper motor is attached to it, and it is remotely controlled by a manual control box. During the vertical scanning, the Dove prism is pulled out of the optical path so that the direction of the separation of two probe beams is parallel to the rotational axis of the rotary table. During the azimuthal scanning, the Dove prism is driven by the micro-motor into the optical path.

The direction of the probe beam separation on the left side of the Dove prism becomes perpendicular to the axis of the rotary table. The final stop position is controlled by a mechanical block, a spring bumper and two micro switches. The adjustment of the rotational Porro prism, polarizer, and the half-wave plate is motorized by using a motorized linear stage and two motorized rotary stages, respectively.

Two penta prisms form an optical hinge so that the directions of the probe beams in the incident and exiting directions stay parallel. The upper penta prism is fixed on the vertical slide. The moving penta prism moves parallel to the rotational axis of the shell mirrors. The moving penta prism, Risley prism pair, and cylinder lens sub-assemblies are combined into the scanning optical head, which is fixed on the vertical arm. The cylinder lens drive assembly consists of a M1524-V-24 micro motor, an eccentric cam, a roller slide and other parts. The cylinder lens is mounted in a lens holder which has a dove tail for initial adjustment. The final adjustment of the cylinder lens is achieved by driving the eccentric cam that pushes the rod connected to the roller slide. The designed maximum distance for the final adjustment is +/- 1.3 mm. The cylinder lens drive assembly is mounted to the frame of the optical scanning head by means of a dove tail. The distances between this unit, the rotational optical wedges, and the moving penta prism can be adjusted. The minimum diameter test object that can be scanned is limited by the mechanical size of the scanning optical head. Currently, we can scan shell mirrors with a diameter as small as 100 mm. Our experimental results show that this structure is very tolerant to the deformation of the slide arm.

9-AXIS MOTION CONTROL

The main tasks in designing the data acquisition are the 9-axis motion control systems shown in Figure 4. The VSLTP instrument contains nine motors that need to be computer/manual controlled. They are: three servo motors for vertical, horizontal, and rotary motions; four micro servo motors for the polarizer, Porro prism, half wave plate, and Risley prisms; and two micro stepper motors for the Dove prism and cylinder lens. A 3-axis motion control card from TECH80 Inc. is interfaced with three servo motors from MFM Technology Inc. and is used to drive the main scan motions.

The other 6-axis control portion is basically used for alignment purposes and involves more customized parts. The microcontroller board consists of the microcontroller and RS232 interface. The computer communicates with the microcontroller board via a RS232 serial interface. The microcontroller board sends commands to the motor controller board which also reads the limit switches to determine the home position and to prevent exceeding the mechanical limits. Currently, a PIC16C74 is used for the prototype microcontroller board. The manual controller can be used in place of the PC to allow the user to control the motors manually. The servo motors are controlled by dedicated precision servo motor PWM drivers. The stepper motors are driven via a data latch and H-bridge drivers. Digital inputs are used for reading limit switches. In the computer control mode, it interprets received commands from PC and sends the proper commands to the motor controller board. It also checks if the commands exceed the physical range of motion and checks the limit sensors during normal operation. The manual controller has a Liquid Crystal Display (LCD) and a keypad. A menu driven program will prompt the user via the LCD for input. Commands and parameters will be input via the keypad. The manual controller is implemented as a subset of the PC program's command set. The PC program follows a handshaking serial communication protocol developed under MS Visual C/C++.

DATA ACQUISITION AND ANALYSIS SOFTWARE

The data acquisition and analysis process is controlled by a PC run under Windows95 operating system. The software is composed of two modules: scan and analysis. The major software concern is to control the TECH80 motion control board and the Princeton Instruments dual array photo-detector. We can only get 16-bit DLL libraries for MS-WINDOWS from these two hardware suppliers. Hence, the software of the motor/scan module has to be programmed under a 16-bit compiler to be compatible. However, the analysis module may be implemented under a 32-bit compiler. The current VSLTP software is designed to run under the Windows'95 operating system so that we may make use of the power of the 32-bit operating system.

The software scan module has the ability of setting hardware parameters for each motor and photo-detector, manual operation of encoder, testing motor motion, auto-operation of motor move, performing stability and data scans. The analysis module includes: converting intensity data to slope data; detrending data (reference correction, polynomial, sinusoidal, and conic subtractions, slope to height and height to slope conversions, edit data and zoom functions); power spectrum analysis; and 3D mapping of the surface profiles and residuals. So far, we have finished programming 3D data conversion and processing, using LabWindows/CVI 4.0 (32-bit) by National Instruments, and programming the motor motion, using MS Visual C/C++ 1.52 (16-bit).

The analysis software is an important part of the prototype VSLTP development. VSLTP is a slope measuring instrument. It measures the minimum position of the intensity pattern reflected from the mirrors under tests. During the scanning procedure, all information on the reflected intensity patterns is recorded in the intensity files. There are two intensity files: one from the vertical scans and the other from the rotary scans. All intensity files should first be converted into the slope files by polynomial curve-fitting to the minimum in the patterns. Then the slope files have to be converted into the height files by integration. For the rotary data, one has to separate the components caused by surface deformation and those caused by the tilt and eccentricity of the mirror or rotary table. In the program, a "Sinusoidal Fit" function is used for this purpose. It subtracts the sinusoidal component of the fundamental frequency in the height profile which is related to the tilt and eccentricity. Other functions in the "Detrend" procedure are similar to those in the standard LTP II products. However, the VSLTP scans the whole mirror surface rather than a line. Even within one vertical scan line, the VSLTP has to scan the paraboloid and hyperboloid segments individually with an offset of the scanning beam produced by the laser beam steering device. In addition, the VSLTP also scans the surface rotationally, and the results from the vertical and rotary scans need to be combined together. All these requirements make the data acquisition and analysis program in VSLTP much more complicated than those in the LTP II. The menu items "Detrend Rotary data", "Detrend Vertical Data" and "3D Analysis" contain three major function groups to construct the surface profiles. To form a 3D mapping of the mirror surface, one has to make a series of scans in the vertical direction, rotating the mirror by a fixed amount between each scan, then turn the direction of the laser beam separation by 90 degrees and scan rotationally. In this way, a mesh of the scanning data with vertical and rotational profiles is obtained. The height data for the cross points from vertical and rotary scans then are synthesized and result in the surface mapping.

FURTHER DEVELOPMENT

The date for completion of the Phase II research is scheduled to the end of February of 1998. Currently, we have finished most of work in design, manufacture and assembly of the optical system, mechanical parts, electronic parts, and the development of the software

for data acquisition and analysis as described previously. We have prepared a shell mirror of 100 mm diameter and a mandrel mirror of 160 mm diameter for testing the prototype instrument. However, we have not yet finished all the work necessary to perform these tests thus are unable to present the measuring results here. The main efforts next will be in design of the reference system to optimally subtract the influence of the tilt and eccentricity on the final slope and height profiles and synthesis of data from vertical and azimuthal scans of the paraboloid and hyperboloid. It is estimated that these results will be ready for publication in March of 1998.

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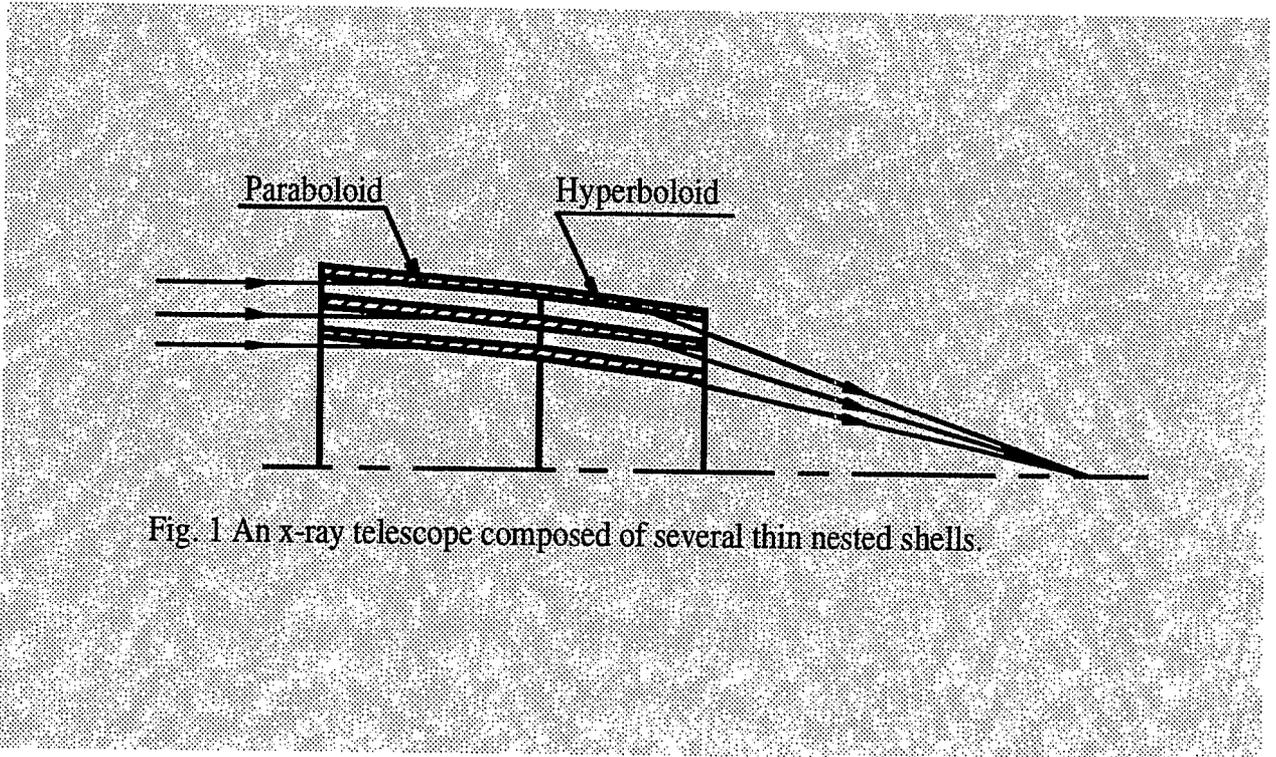


Fig. 1 An x-ray telescope composed of several thin nested shells.

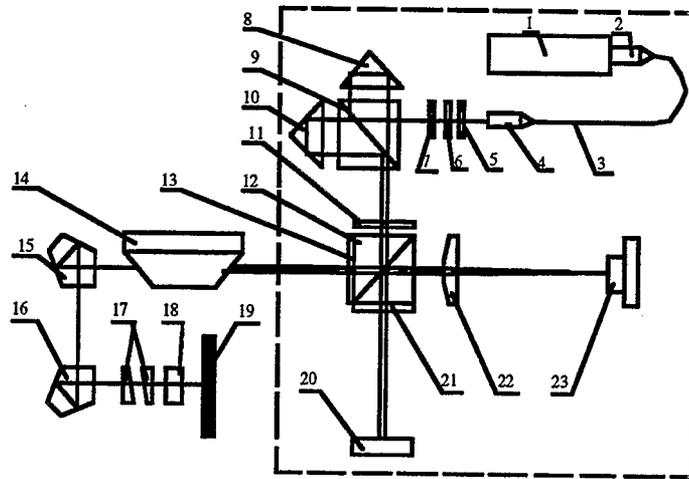


Fig.2 VSLTP optical system:

1. HeNe laser head; 2. Collimator; 3. Fiber; 4. Collimator; 5. Fixed polarizer; 6. Rotational polarizer; 7. Fixed polarizer; 8. Porro prism; 9. Non-polarizing beam splitter; 10. Porro prism; 11. Half-wave rotational plate; 12. Polarizing beam splitter; 13. Quarter wave plate; 14. Dove prism; 15. Penta prism; 16. Moving penta prism; 17. Risley prism pair; 18. Cylindrical lens; 19. Mirror under test; 20. Reference mirror; 21. Quarter wave plate; 22. Fourier transform lens; 23. Photo detector;

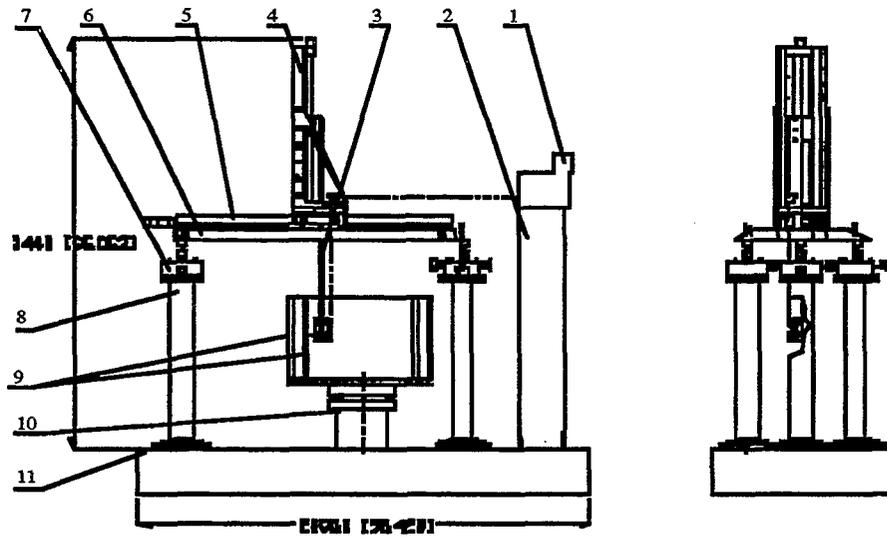


Fig. 3 Main parts of the Vertical Scanning Long Trace Profiler:

1. Optical head; 2. Support; 3. Vertical arm; 4. Vertical slide; 5. Horizontal slide; 6. Frame; 7. Kinematic mount; 8. Legs; 9. Nested shell mirrors; 10. Rotary table; 11. Optical table;

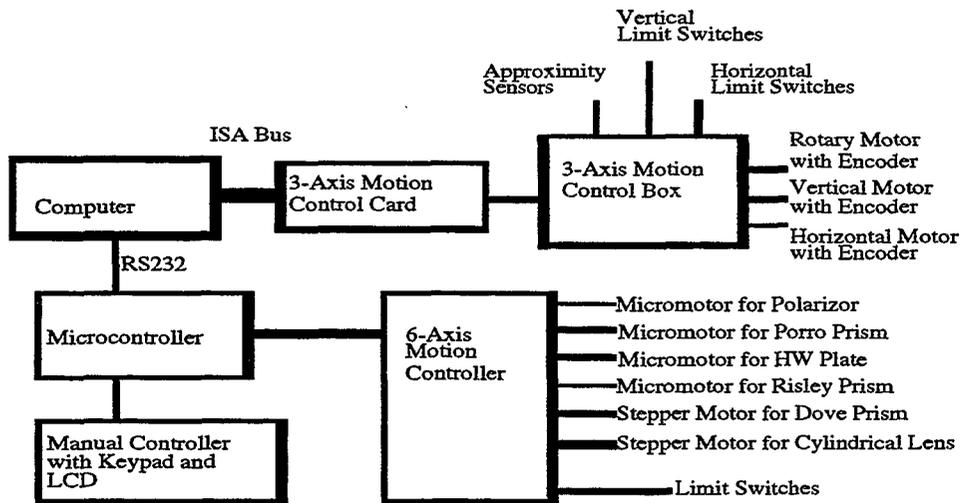


Fig. 4 Diagram of the 9-axis motion control system.