

CHAPTER 2: THREE DIMENSIONAL TOPOGRAPHICAL MAPPING SYSTEM

2.1 Theory and Construction

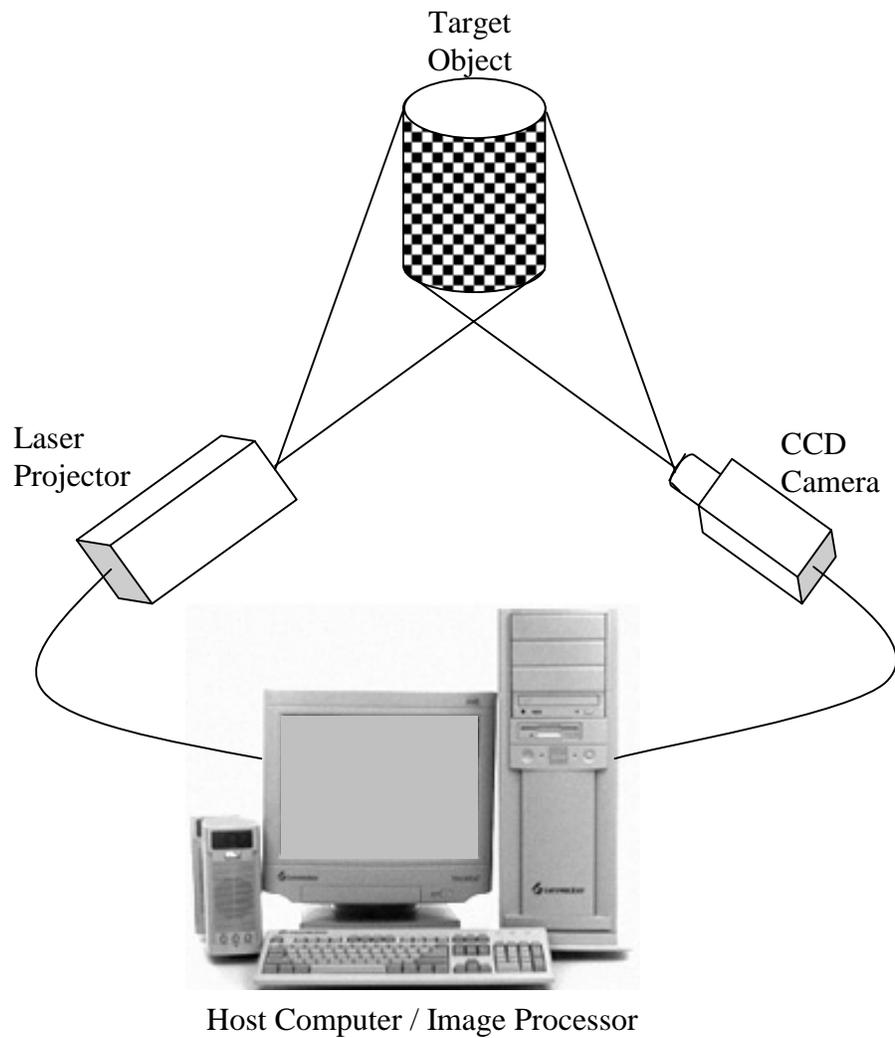


Figure 2.1 Block Diagram of 3D Areal Mapper

The basics of 3D topography involves illumination of the target object with a sequence of optical patterns, acquisition of the image of the patterns reflected from the object, and using the acquired data to extract information about the surface. The pattern is usually generated by directing light from a laser source at an interference fringe generator such as a hologram. The pattern can be a single line, a set of parallel lines, or an array of dots. The pattern is then passed through a shutter

mechanism, such as a Spatial Light Modulator (SLM), to switch "on" and "off" the individual lines or dots, to form a temporal series of patterns. The sequence of patterns is projected on the object one after the other without altering the position of the object and the reflected images are captured using a video camera. Once the entire series of images is acquired, the collected data is processed to extract the 3D information.

The basic block diagram of the 3D Areal Mapper developed by DCS Corporation is shown in Figure 2.1. The system has three major blocks: a system for projecting the laser patterns on the object of interest, an optical image recording system, and a computer to interface the laser projecting system with the image recorder and to perform data processing.

Laser pattern projector

The laser-pattern projector functions as a structured light source for the 3D Areal Mapper system generating an $M \times N$ (M and N are usually powers of 2, such as 64, 128 or 256) beamlets pattern. The light source used in the projector is a laser diode with output in the visible range. The output from the laser is coupled through a Polarization Maintaining (PM) fiber to a hologram. The function of the hologram is to expand and partition the primary laser beam into a two-dimensional array of $M \times N$ beamlets. The output pattern from the hologram is then incident upon an SLM. The SLM turns "on" and "off" the individual beamlets of the $M \times N$ pattern, depending on the control signal from the host computer, and thereby generating a sequence of predefined patterns. These patterns are then projected onto the object of interest one after the other using an output-coupling lens, which is used to vary the size of the pattern and to vary the distance at which it is projected.

Optical image recorder

The images of patterns reflected from the object are captured in digital format using one or more CCD video cameras. The number of cameras depends on the number of perspective angles in which the image of patterns has to be captured. Furthermore, depending on the wavelength of the laser source used in the projector, special wavelength-specific optical filters are used in the

cameras. The digital data from the camera(s) is transferred to the host computer either directly or through a high-speed buffer. The buffer stores the data from a sequence of patterns and transfers the entire set as a single entity and thus increases transfer rate.

Host-computer

The function of the host computer is to perform hardware synchronization between the LIM and the CCD cameras; to perform software image processing using data obtained from cameras to extract 3D information about the object; and to identify any error in the profiling operation. The software used for image processing rapidly decodes the digital data obtained from the cameras and provides information such as the position of a pattern on the surface, motion of the object with respect to a reference, and complete 3D projection of the object.

2.2 Motivation

The 3D Areal Mapping system proposed by DCS Corporation was based on the Numerical Stereo Camera System (NSCS) [6]. The NSCS used an Nd:YAG diode-pumped laser to generate a 128 x 128 pattern as the output from laser projector. The projector was a large device that was about five feet long. It had a number of glass elements that needed to be aligned in a rigid manner and hence needed an extensive positioning system to prevent disturbance due to environmental vibrations. DCS Corporation reduced the size and complexity of the projector by using their patented hologram technique [6]. The prototype developed using this principle was about 18 inches high and occupied a 3' x 2' optical bench. The prototype assembly included the laser projector and the motion stage for the object. The laser projector was divided into two separate blocks. A He-Ne laser functioned as the light source and the box containing the hologram, the SLM, and output-coupling lens functions as the laser projector. The object whose 3D information is required was mounted on a stage capable of being moved in x, y, z, and theta directions. The prototype had a reference object that was used for calibration purposes. The laser projector occupied a 1' x 2' optical bench.

DCS Corporation identified potential applications for its areal mapping system in the area of biometrics and in the jet turbine industry. However, this required a system of much smaller volume with a beamlet array output pattern of higher power. A smaller system provides better portability and can be mounted on equipment that required easy maneuverability such as in surgical instruments. A beamlet array output pattern has information corresponding to both the horizontal and vertical directions and hence has more information when compared to a pattern of parallel lines. Furthermore, since more information is transferred in each image, video bandwidth efficiency is improved. Increase in the information transferred also results in increasing the resolution of the surface profiling output and hence an improvement in the accuracy. A higher output power results in a higher signal-to-noise ratio of the image captured by the camera. Thus, the above improvements increase the feasibility of using the system for commercial and industrial purposes.

2.3 Light Illumination Module (LIM) - Principle of operation

In the DCS 3D mapping system, the laser projector consists of a single mode fiber pigtailed diode laser system and a LIM. The major components of the LIM and their arrangement are shown in Figure 2.2.

Beam Array Pattern Generation

The diode laser/fiber system with an output power of 15mW at the wavelength of 690 nm, is used as the light source. The output from the laser system is coupled to the LIM by a tiny lens pigtailed with a PM fiber cable. The amount of laser output coupled to the PM fiber is varied using a 6-screw adjustment mechanism. The maximum typical coupling is 50% for polarization ratio larger than 20dB. While one end of PM fiber is pigtailed to the laser diode's output, the other end is fitted with a FC type fiber connector. The fiber connector is used to connect the PM fiber to the LIM through a 5 dimensional fiber optic positioner. The linearly polarized light out of the PM fiber is then projected onto the hologram, which generates four virtual point sources. The point sources are located in the four corners of the square and they interfere to form a coherent array of 256 x 256 beamlets. It is essential that the alignment of hologram in LIM is the

same as its alignment during fabrication in order to obtain an output with the desired square dot pattern of high energy. The hologram is mounted on a 20degree rotary support with a mount. The mounts allow the hologram to be rotated along its own plane. The rotary stage containing hologram is then mounted on a rotation stage to provide the capability of 360° rotation of hologram in the vertical plane. These two degrees of rotation ensure proper alignment of the hologram.

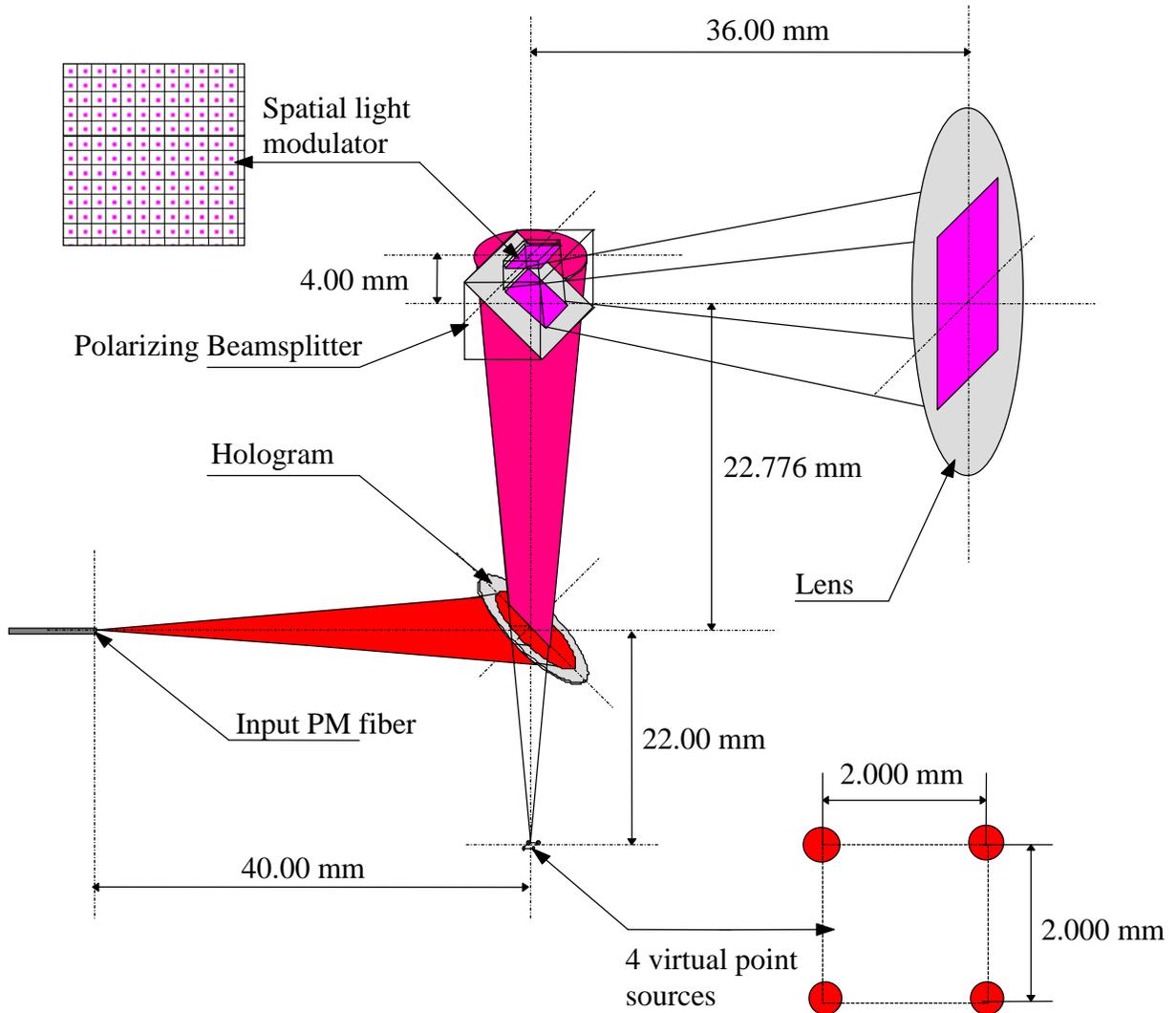


Figure 2.2 Laser Illumination Module

Beam Array Coding

The beam array output from the hologram is directed onto the SLM-beamsplitter combination. The SLM is a liquid crystal device in which the ferroelectric cells are arranged as a two dimensional array of 256 x 256 pixels. The polarization of the light falling on the SLM pixel is retained or rotated by 90° depending on the control signal applied to each pixel by the host computer. The output from each pixel when passed through a polarizer will appear to be turned either "on" or "off" depending on its polarization, thus generating different patterns. The incident as well as the reflected light of the SLM passes through a polarizing beam splitter. The beamsplitter, in addition to acting as the polarizer ensures normal incidence of the SLM input onto the corresponding pixels. The beam splitter is glued directly to the SLM using epoxy and the beam splitter-SLM combination is mounted on a special holder designed at FEORC. A six dimensional adjustment stage is used to hold the SLM mount and to align it with the laser array. The adjustment stage is removed after aligning the SLM and cementing the SLM holder to the base.

Beam Array Projection

Depending on the size and distance of the object to be profiled, a suitable output-coupling lens is selected. In the system delivered to DCS, a lens of focal length 50mm is used. The CL mount is used in combination with the standard focussing mount to allow usage of a different lens in order to obtain the optimum structured light output. There is provision for the lens to be moved back and forth until the SLM is positioned at the focal plane of the lens to form a clear pattern of beamlets as output.

LIM Box

The entire optical arrangement is placed inside a 6.0inch (L) x 5.0inch (W) x 3.8inch (H) box. There is a slot in rear wall to insert input PM fiber while the output is coupled through the coupling lens in the front wall. The circuit board that functions as the driver of the SLM is fixed

to a side of the box with four screws. There is a slot on the same side of the box for the cable connecting the driver to the SLM. The LIM box is fixed to the tripod using two ¼-20 threads, one at center of the base, and the other on the center on the side wall that is opposite to the wall holding the circuit board. The box is painted in black to prevent multiple reflections.

2.4 Research Contribution

The contribution of this thesis is to improve the output power and resolution of the areal mapping system, while maintaining its size to a minimum. A diode laser/fiber illumination system is designed and fabricated, to improve the output power of the LIM and to reduce the size of the existing laser source. An SLM is selected to improve the resolution of the mapping system and its driver is designed to keep the volume of the LIM to a minimum.

The diode laser/fiber illumination system designed and fabricated has the following advantages over the He-Ne laser source used by DCS.

Smaller Volume: Based on specific electronics and system design, a complete laser/fiber/electronics system is fabricated with a volume less than 73 cubic inches. This laser source is much smaller than the He-Ne laser, which is half meter in length and has to be driven by a high voltage power supply.

Higher Power: The laser system uses a high power laser diode capable of 30 mW output power. Advanced optical coupling technique is used to couple the output from the laser diode to a polarization maintaining (PM) singlemode optical fiber. The resulting optical power out of the pigtailed optical fiber is 15 mW, which is twice the output power from the He-Ne laser system used by DCS.

Less Cost: After extensive research, the laser system is successfully fabricated for a total cost of less than \$2,000 whereas, the DCS' He-Ne laser system costs about \$8,000.

Independent Module: A 3m fiber pigtailed to the laser diode allows the freedom of separating the source from the actual LIM. Since the laser diode is not included within the LIM, the size is greatly reduced. The laser source is independent of the LIM and hence any malfunctioning of the laser can be rectified without disturbing the LIM.

The SLM used in the existing DCS areal mapper has an output pattern of 64 parallel lines. A number of commercially available SLMs were studied to identify one with improved resolution, while having a smaller volume and better power efficiency. The SLM used in the LIM has an output pattern of 256 x 256 beamlets, and has an optical throughput better than 25%. The SLM can be mounted on a regular 2" optical mount. The driver electronics designed for the SLM can be mounted on the wall of the LIM, thus eliminating the need for a separate box and reducing the overall area occupied by the system.

2.5 Advantages of LIM

The specifications of the LIM supplied by FEORC are listed in Table 2.1.

Table 2.1 LIM Specifications

| FEATURE | SPECIFICATION |
|--------------------------------|----------------------------------|
| LIM size (not including laser) | 6.0" (L) x 5.0" (W) x 3.8" (H) |
| Beamlet output format | 256 x 256 |
| Laser power at exit aperture | 1 mW integrated over active area |

The main advantages of the LIM are its compact size and its lightweight. It is small enough to be mounted on a moving mechanism and can be used to profile both small and large objects. The laser source used is a relatively small diode laser that does not require separate cooling mechanism and hence can be used in applications which require operation at room temperature. All the parts in the LIM are fixed and they do not need any future alignment. Hence, it saves time and can be used in applications with critical setup time. The structured light output from the LIM has infinite depth of focus and can be used to cover a wide area of the object with its 256 x 256 laser spot output. This has several advantages over a system that outputs a single laser line or single row of laser spots. The obvious advantage is the effective use of resources, since in a single line system, the laser line uses only a small portion of the available image bandwidth. The other advantage stems from the factor that the laser projector or the CCD camera needs to be moved 256 times in a single line system to cover the area covered by a single pattern from the LIM. A 30 frame-per-second CCD video camera is used in most applications and in the case of the single line system, the next line has to be imposed at the exact position between the available

frame capture duration. This is not feasible and it results in smearing of the image and hence a loss in accuracy of the profiling information.

2.6 Applications of LIM

The LIM can be used in a 3D profiler to obtain information about a broad range of surfaces, which includes the body of patients during treatment and surgery. Other applications include rapid prototyping, 3D digitization for computer animation, and turbine blade rework.

The LIM will be used by DCS Corporation in its development of the 3D Patient Registration system for medical applications where patients must be precisely positioned relative to operating room treatment equipment. The system is to be used for biometric purposes to obtain profile information about different parts of a patient's body. This profile information is to be used for patient positioning in radiation oncology and deep-lesion neurosurgery treatments, which were discussed in Chapter 1. The 3D Patient Registration system will offer unique features [6] such as continuous 3D patient maps over broad areas, on-patient display of position disparity symbology, insensitivity to tissue reflectivity and texture, and tolerance to surface irregularities.