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**A FULL-COLOR, HIGH-RESOLUTION LASER PROJECTOR
FOR A FLIGHT SIMULATOR VISUAL DISPLAY**

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13. ABSTRACT (Maximum 200 words) Laser projection is a promising approach to solving many of the shortcomings associated with current flight simulator projection methods. The advantages of laser projection were investigated and are discussed. The characteristics of light valve, cathode-ray tube (CRT), liquid crystal display (LCD), and laser projectors are compared. It was found that laser projection offers many benefits over current projection technology. Laser projection promises an increased color gamut, higher luminance, zero persistence, and increased line rate. The technology required to develop an efficient, cost-effective laser projector was researched and is described. Recent advances in laser diodes, solid-state diodes, and other rapidly developing technologies and techniques promise new territory for laser projection. It is concluded that laser projection is a promising solution to the shortcomings of flight simulator visual displays and that the technology now exists to develop an efficient, cost effective laser projector.			
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CONTENTS

	Page
INTRODUCTION.....	1
WHY A LASER PROJECTOR?.....	2
CURRENT LASER PROJECTION TECHNOLOGY.....	8
CAN WE DO IT?.....	11
CONCLUSIONS.....	16
REFERENCES.....	17

List of Figures

**Fig.
No.**

1	Color Gamut of Laser Projection Display.....	3
2	Night Vision Goggle Light Characteristics.....	7
3	Schematic of a Volumetric 360 ⁰ Display.....	10
4	Major Components of a Laser Projector.....	12
5	Rotating Polygon Laser Deflector.....	14

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PREFACE

This investigation contributes to the development of cost-effective, high-fidelity, flight simulation visual display technology. For a pilot to perform air-to-air, air-to-ground, and terrain-following fighter aircraft maneuvers in a flight simulator, it is important that the out-the-window visual provide bright, properly defined targets and scenery. This investigation addresses this critical requirement for development of a cost-effective, high-fidelity, visual display system.

Technology discussed in this report also addresses recent legislation promoting dual-use technologies in the Department of Defense (DOD). This technology may lead to developments in future high definition television and other visual display applications. It also could promote small business innovation research (SBIR) and other cooperative efforts that maximize benefits obtained through DOD research and development investments.

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A FULL-COLOR, HIGH-RESOLUTION LASER PROJECTOR FOR A FLIGHT SIMULATOR VISUAL DISPLAY

INTRODUCTION

Flight simulator displays at Armstrong Laboratory have recently used light valve projectors, liquid crystal display (LCD) projectors, and high resolution cathode-ray tube (CRT) projectors to present the out-the-window visual scene. Relatively high-cost light valve projectors have been the mainstay of flight simulator visual displays for years. LCD and CRT high resolution (1,026 x 1,026 line) projectors have led to less expensive flight simulator displays, but other simulator components, such as computer image generators and microcomputers, have matured at a much greater pace. As a consequence, displays often limit simulation fidelity and make certain training tasks in a flight simulator difficult if not impossible. Introduction of an advanced projection system would certainly bring a welcome boost to flight simulator visual display capability.

Laser-based projection is a promising technology that may resolve many of the problems associated with current projection methods. Laser light has many characteristics that make it an ideal light source for an advanced visual projection system. Laser light is far more directional, powerful, and coherent¹ than any other light source. Lasers produce an intense beam that is very pure in color. Laser-produced red, green, and blue primary wavelengths plot on the boundary of the ICI (CIE) chromaticity diagram; a characteristic that allows a very large gamut of colors. Unlike deformable oil films, phosphors, and LCDs, a laser has zero persistence. Moving images in a laser display will not smear or blur.

In recent years, foreign and domestic laser suppliers have aided the development of various laser-based projection devices. Federal Aviation

¹Coherent light is light of a single frequency or color in which all components are in step with each other.

Administration (FAA) and other military training programs have developed and used laser projection systems. The size and inefficiency of earlier lasers has kept laser projection from achieving widespread use, however, recent developments in laser technology promise new territory for laser projection systems. Less expensive and more efficient lasers are rapidly becoming available. Devices and techniques leading to new and improved capabilities are continuously being developed.

Laser projection presents a promising approach to producing brighter, higher resolution, high-contrast, out-the-window scenes. Such a system would not only improve flight simulation and training, but it would also have the potential to stimulate improvements in other display applications as well.

WHY A LASER PROJECTOR?

Examining the characteristics of current technology will help to understand the benefits gained from a laser projector. Light valve, CRT, and LCD projectors are capable devices that have been used in flight simulator and other visual displays for years, yet, they have considerable shortcomings. When the requirements for luminance, resolution, contrast, and saturated colors increase, the shortcomings of current technology become apparent. The characteristics of laser light make it an attractive solution.

Color light valve, CRT, and LCD projectors use the additive combination of red, green, and blue primary colors to produce their available colors. A CRT achieves the three primaries by exciting red, green, and/or blue phosphor dots placed on the display surface. In a CRT projection display, the images from red, green, and blue monochrome CRTs are combined to create a single full-color display. An LCD projector optically combines the output from red, green, and blue LCD panels to produce color. A light valve extracts the three primaries from a single xenon light source. As light passes through dichroic filters it is converted into green and magenta (red and blue) light. Not only does light valve, CRT, and LCD technology differ, but so do their color characteristics.

Figure 1 gives a representation of the differences in color characteristics of a light valve, CRT, and laser projector. Since the color gamut of any particular projection can be manipulated easily with filters, phosphors, etc., the color gamuts shown in Figure 1 should only be considered as representative. However, as Figure 1 shows, the color gamut of a laser display is typically much larger. This maximizes the color space available for displaying highly saturated colors. The color gamut of a particular laser display depends on the wavelengths of the lasers used in the system. But because laser primary colors are so pure, changing the wavelength just slides the triangle corners along the boundaries of the CIE diagram (Jachimowicz, 1992).

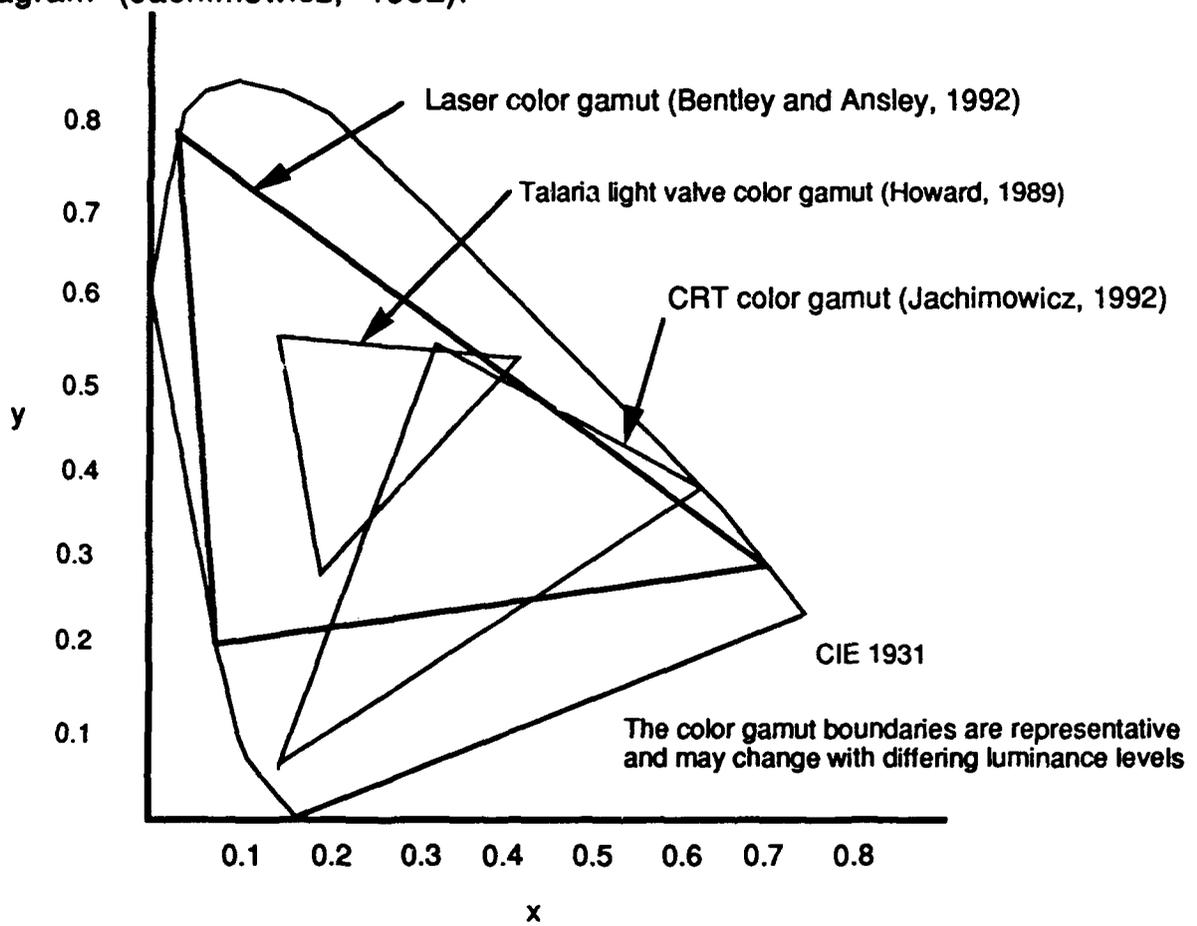


Figure 1
Color Gamut of Laser Projection Display
Using Green at 514 nm, Red at 647 nm, and Blue at 488 nm

Pure colors from lasers also enable chroma multiplexing. Narrow band rejection filters can be placed on the trainee's visor to prevent him/her from seeing another scene being projected on the same display by a projector using different red, green, and blue laser wavelengths. Trainees such as a pilot and weapon systems officer could train in the same display with different and noninterfering scenes (Bentley & Ansley, 1992). With the use of filters that pass/reject different wavelengths placed over the goggles, the pilot/weapon systems officer is able to see his own display without interference from the other trainee.

Light valve projectors are favored for flight simulator domes and other displays because of their ability to project scenes with both high luminance and high resolution. Light valve projectors output around 2000 lumens. Yet, recent research has shown that luminance levels in the limited field of view (LFOV), 24-ft diameter dome at Armstrong Laboratory's Aircrew Training Research Division, which use Talaria light valve projectors, is more like moonlight than daylight, no matter what type of scene is being presented (Howard, 1989). Light losses in the LFOV display are certainly a contributing factor. However, if a display such as the LFOV dome is to be considered high fidelity, a projector with much greater luminance output is required. Other domes are known to exhibit even greater attenuation. In addition, as the xenon arc tube source in a light valve projector undergoes aging, the luminance output continually declines. Luminance levels from current light valve technology may be the highest available, but they fall short of providing the luminance levels required for many visual display systems. Their relative high cost make them even less desirable.

CRT and LCD projectors are finding favor in many of the new low-cost visual displays. Luminance has improved while cost has declined. CRT projectors typically output between 300 and 1500 lumens, depending on the performance and cost of the system. However, major increases in the luminance output of a CRT projector may be difficult to achieve. Luminance levels from a CRT are limited by its inverse relationship to resolution. To increase the luminance of a CRT, more electrons are required, resulting in a larger electron beam that lowers the resolution of the CRT. LCD projectors have less luminance than a light valve or CRT. Recent models claim outputs

between 300 and 1,000 lumens. The development in this area has been substantial and is still very competitive. However, it remains questionable whether CRT and LCD projector technology will ever be capable of providing the luminance required for many flight simulator visual displays.

Light emitted by a laser is coherent in nature and therefore much more directional or concentrated than the noncoherent light sources used in light valve, CRT, LCD, and other displays. An obvious benefit of this is the ability to obtain higher luminance. Luminance of a laser display is dependent upon the power of the laser(s) used and the light throughput of the display system. As laser technology improves so will the luminance levels of laser projectors. In general, the luminance of a laser display would be orders of magnitude greater than systems using noncoherent light sources.

The coherency of laser light provides other benefits as well. Because of its coherent nature, laser light can be focused to a very small spot -- a characteristic that would support higher line rates. Laser light can be focused to such a small spot, that de-focusing is often required. Laser light can also be collimated so the distance to the screen does not affect focus -- a characteristic that would be useful in many applications.

A current technology projector is considered high resolution if it projects a 1,026 x 1,026 line rate. Referring to these projectors as high resolution may be misleading. Much higher line rates would be extremely useful in a flight simulator. Higher line rates would increase the line density² and improve the visual acuity of the display. With current projection methods, the pilot in a simulator often spots a long-distance target first by the halo rather than distinguishing the target itself. This obviously reduces realism. Image generators can be procured that output

²Line density is the number of lines per unit of space. With all other variables the same, a 2,000 line projected image would have twice the line density as a 1,000 line projected image. An image with higher line density would have increased definition.

images with line rates exceeding 1,026 lines, however, there is no way to project it. Improving the line density of the display by adding more channels of imagery would be costly and just disguise the problem. Developing a projection system with much higher line rates than current technology is the key. Laser projection may be the answer.

The line rate of a laser projector is governed by how the laser beam is deflected. There are various ways of deflecting the laser beam in a laser projector. Laser beam deflectors will be discussed in a later section. But it appears that the technology exists to develop a laser projection system that would project a 5,000 x 5,000 line image. This would be a major advantage. Higher line density could be obtained with less channels of imagery, but more important, the capability would exist to present a visual scene that would give simulator pilots the ability to identify air and surface targets and their attitude with similar fidelity and realism as in the aircraft.

Night vision goggle (NVG) training has taken on greater importance in recent years. Because visual acuity is so much better at night when wearing NVGs, everyone tends to think they can see better than they really can. Under certain circumstances this can lead to dangerous situations. Being able to train with NVGs in a simulator under realistic conditions would be highly desirable. NVGs produce an image by amplifying low-level light and near-infrared (IR) energy that is reflected/radiated from objects (See Fig. 2). A laser projector with near infrared capability would project wavelengths from visible through mid-infrared exciting the full light spectrum of the NVGs. It is understood that NVG simulations are affected by various technologies other than the display system. Yet, it seems safe to say that a laser projector would bolster an NVG training system and at least serve as a competent component of such a system.

A characteristic found in many displays using current projection technology is persistence. Phosphors, oil films, and LCDs all have decay times and therefore produce persistence. Because of the way LCD projectors obtain their brightness, they exhibit the most persistence. Unlike all of these, laser displays have zero persistence. Moving images in a laser display will not smear, blur, or leave a trail. Zero persistence provides

other benefits as well. Switching between images or projector boundaries would occur very rapidly. A projector with zero persistence is ideal for highly dynamic visual displays such as head- and/or eye-tracked display systems.

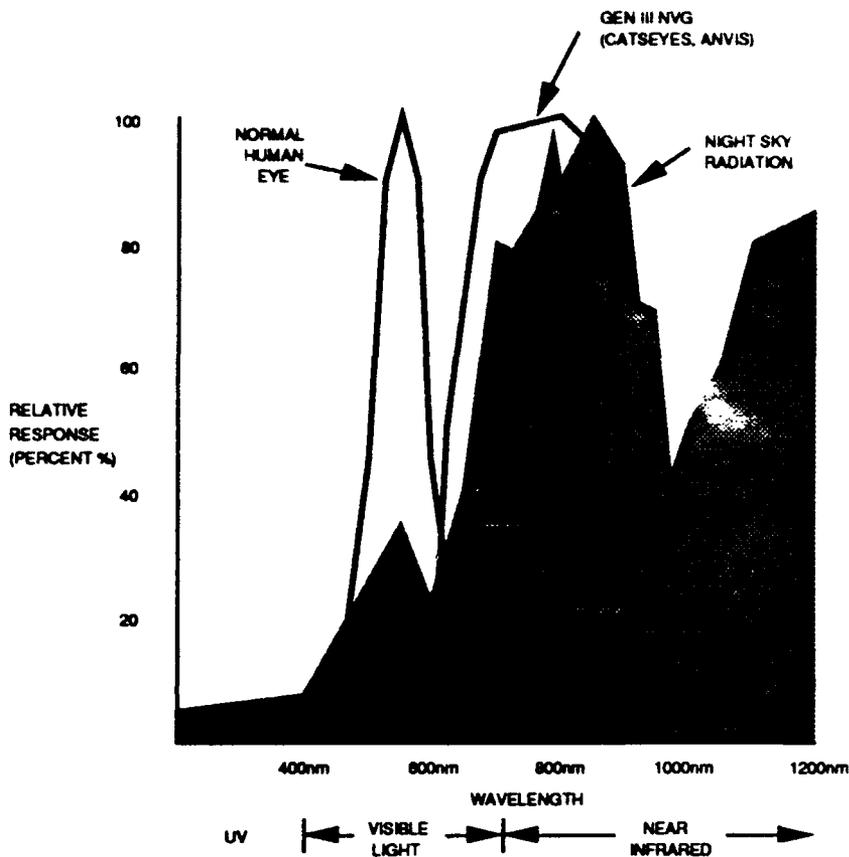


Figure 2
Night Vision Goggle Light Characteristics

Laser projection offers many benefits and advantages over current projection technology. Benefits include increased color gamut, higher luminance, zero persistence, and increased line rate. All of which, would significantly improve display technology and lead to brighter, higher contrast, more realistic flight simulator visual displays. There have been major advances in CRT and LCD projection technology in recent years. But compared to the advantages that could be obtained from a laser based projection system, current technology is clearly limited. Laser projection offers a level in display technology that is simply not attainable from current projection methods.

CURRENT LASER PROJECTION TECHNOLOGY

The word laser is an acronym derived from "light amplification by stimulated emission of radiation." Einstein recognized the existence of stimulated emission in 1917. It was not until the 1950s that ways were found to use it in devices. Several U.S. and Soviet physicists proposed related ideas. The first laser, constructed by the U.S. scientist T.H. Maiman in 1960, used a rod of ruby. Since then many types of lasers have been built and are available for a wide range of application. They vary in size and power requirements depending on their use.

In 1988 the McTavish Company of England with assistance from Lincoln Laser Company of Phoenix, Arizona developed a laser projection system for large hotels in Europe. This system uses a five watt Ar-Kr laser to project a 12-ft x 6-ft scene from 20 ft away in the standard European format of 625 lines at 50 Hz. An Ar-Kr laser emits light at two wavelengths. One at 450 nm (blue) and the other at 670 nm (red). Green is produced by a dye laser. At that time, dye lasers had only 13% power output efficiency. The other 87% of the power was radiated away in the form of heat. Because of this and other inefficiencies, a water cooling system was required that made this innovative projector overly large and bulky. Fortunately, recent developments in lasers should alleviate the inefficiencies and decrease the energy, cooling, and size required for a laser projector.

For some time, flight simulators have used laser projection systems to project targets onto a scene. A system developed for the FAA's air traffic control trainer uses twelve small lasers to project twelve moving targets onto a wide angle visual background of an airport. Laser target projectors continuously draw the target as the projector is moved and focused appropriately for each target's location in the scene. Some are capable of using television raster or calligraphic scanning to produce effects such as afterburners, missile launch flash, infrared decoys, and navigation lights. These projectors are useful with systems where the background does not move or change rapidly. When used properly, these projectors can be very

effective. Similar projectors generate the colorful laser light shows seen at many entertainment events.

Hughes Aircraft Company has developed a laser projector that displays two full-color targets and one monochrome target, and provides non-interfering night vision goggle training for both the pilot and weapon systems officer. This system generates colors with an Argon laser for blue and green and a dye laser for red. A near-IR laser is used to generate IR images. A polygon mirror provides a scanning mirror surface that generates the horizontal sweep for the display. One polygon mirror provides three independent horizontal scans. Each horizontal scan is 960 pixels wide. A galvanometer and associated mirror provide the vertical sweep for the display. There are 875 TV lines. During night vision goggle training, the pilot and weapon systems officer train in the same dome wearing goggles. Near IR lasers operating at different wavelengths provide two independent undistorted images. With the use of filters that pass/reject different wavelengths placed over the goggles, the pilot and weapon systems officer are able to see their own display without interference from the other trainee. A 40-degree target size, combined with headtracking, allows the pilot/weapon systems officer to utilize night vision goggles at full dynamic range and be safely exposed to the effects of blooming and automatic gain control (Bentley & Ansley, 1992).

Volumetric 360-degree displays with helical and flat screens are using HeNe and other lasers to present a real-time, 3-D image. Volumetric displays consist of various shapes of screens that are continuously moved or rotated. An image is projected onto the continuously moving screen. As the screen moves, the image is changed to accommodate the new spatial relationships. Over one period the image seems to occupy the same space as the moving screen (See Fig. 3). In this display, a radial scanner consisting of two mirrors fixed to a balanced rotating arm is coupled to the screen and spins in unison with it. The HeNe laser beam containing the image information travels along the rotation axis, is reflected from the first mirror to the second mirror, and then reaches the screen (Bains, 1993). An

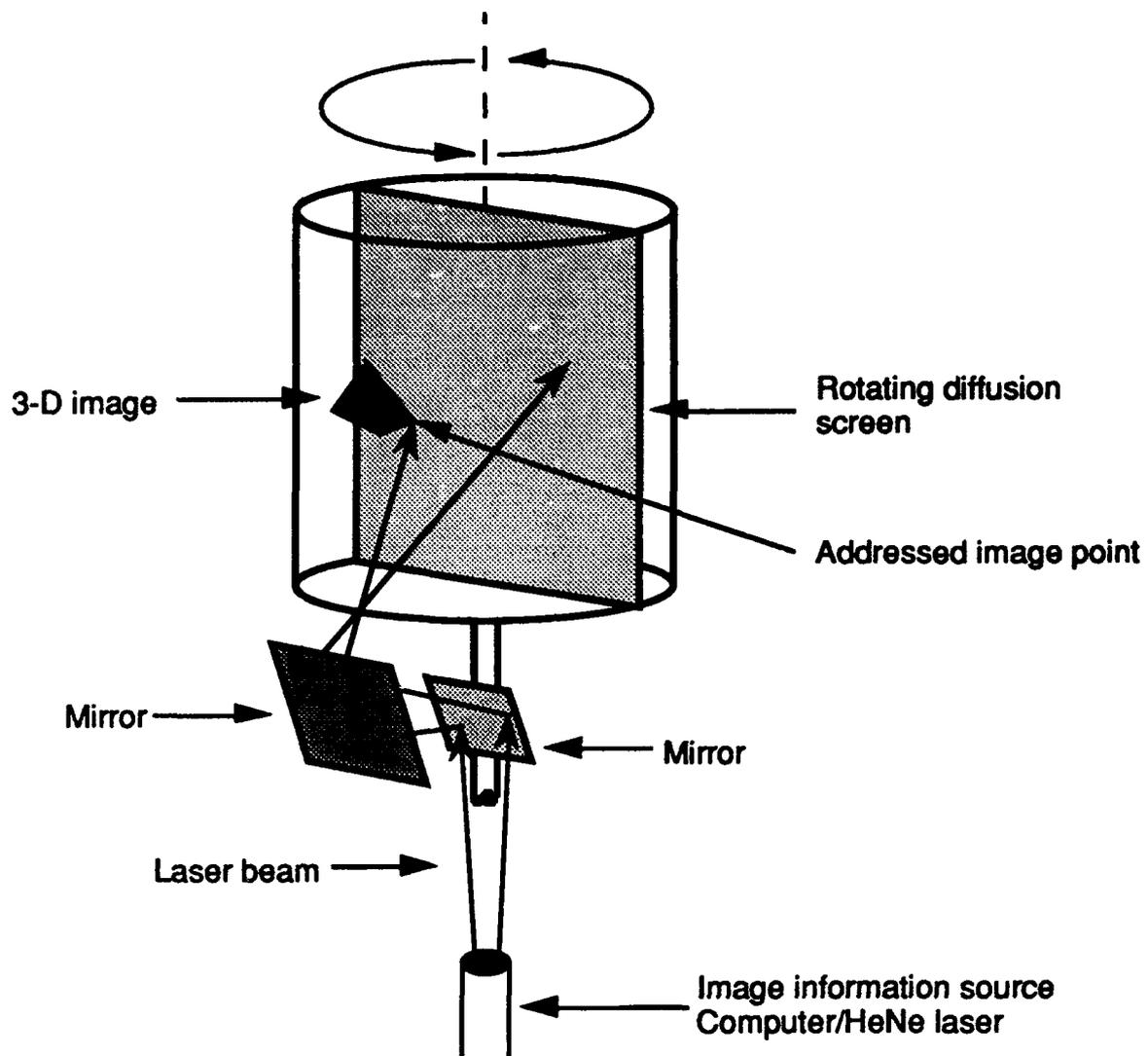


Figure 3
Schematic of a Volumetric 360-Degree Display

image that can be seen through 360-degrees is produced. Some volumetric displays utilize a fixed scanner.

The Naval Training Systems Center (NTSC) in Orlando, Florida has been actively developing laser based projection systems since the early 1980s. They have demonstrated that a laser projector can have greater resolution and higher contrast than existing systems. NTSC has built and validated a low-cost, low-power laser television using the U.S. standard format of 525 lines at 60 Hz. They are also developing a helmet-mounted, head-tracked

laser projector for projecting a full-color scene onto the surface of a dome. The system will display 1,000 lines and they expect a contrast ratio of 30:1. Colors are generated with an Argon laser and a dye laser.

These systems are interesting and give a sense of what could be accomplished with an advanced laser projection system. Displays would present high-contrast, true-color day and night presentations. Along with the many benefits associated with lasers, the same system could present an image in the IR spectrum for night vision goggle training. If noninterfering displays for a pilot/weapon systems officer is required, that could be done as well.

The difficulty will be in developing a system that is efficient and portable. Luckily, laser technology and techniques are advancing at a great pace. Recent advances in laser diodes, solid-state lasers, tunable lasers, and techniques such as solid-state diode pumping, optical combining of laser diode outputs, and frequency doubling have matured to where an efficient and portable laser display seems attainable. The time has come to take the next step. The question is: Can we do it?

CAN WE DO IT?

Raster laser projection systems utilize a scanning laser beam that operates in a similar manner as the electron beam of a CRT. Unlike a CRT, the screen does not luminesce; instead laser light is diffused onto a screen. A laser projector consists of several components (See Fig. 4). Components include: the laser light sources, modulators that encode the laser beam with intensity variations corresponding to the video information, and deflectors that provide horizontal and vertical scan of the laser beam. Full color laser displays use separate laser wavelengths for each primary color. Each primary is properly encoded by its modulator, and then combined with the other primaries for presentation. The horizontal and vertical deflectors then place the laser beam at the proper location on the display. Images requiring near infrared laser wavelengths are presented in a similar manner.

As mentioned earlier, laser projection systems have been limited primarily by laser light sources that required large input power and a cumbersome cooling system. With recent developments in laser diodes and solid-state laser diodes, we now have the potential to make small, highly capable laser displays a reality.

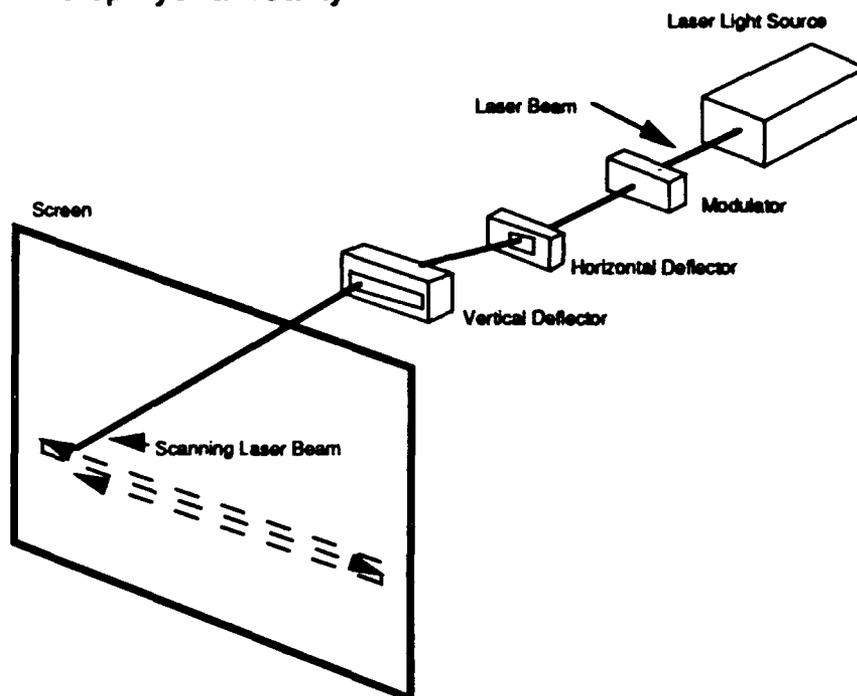


Figure 4
Major Components of a Laser Projector

A laser diode is fundamentally a small integrated circuit (IC) that uses a current to cause it to emit coherent light. Solid-state laser diodes are similar except that they are constructed of three or more components. Laser diodes are normally made from silicon. Solid-state diodes are generally used as a pumper. Diode pumping is a term for exciting a crystal or gas with a frequency that causes it to laser. A major advantage of laser diodes and solid-state laser diodes is they are relatively inexpensive and operate at room temperature. Since they became available in visible wavelengths, the choice of wavelengths and output power has steadily increased. There are now solid-state lasers that have an output power of one watt or greater.

Estimates predict that 1.47 watts (1,000 lumens) per primary would be required at the screen for a high luminance (3,000 total lumens for day) laser display. Attenuation of the beam caused by optics in the display system using a laser projector would require even greater power. Assuming approximately .25 losses, a laser primary of 2 watts should be sufficient. Laser diodes and solid-state laser diodes with this energy may be developed in the near future but are not currently commercially available. To reach the required power, some type of light amplification would have to be utilized until small and efficient lasers producing the required energy are developed. Light amplification is a technique that is also being rapidly developed.

A light amplification method showing promise is optical combining of multiple laser diodes. This technique increases the intensity of the output beam without altering the wavelength.

A modulator, synchronized with the laser beam deflectors, encodes the laser beam with video information. Image information feeds into the modulator where the intensity of the laser beam is electronically controlled. There are various ways of doing this. Electro-optic, acousto-optic, and deformable mirror modulators are the most common. Modulators for 1,000- and 2,000-line scenes have been demonstrated -- 5000-line modulators should be achievable. Each source (primary) would require a modulator. Laser beams from the three modulators (representing the three primaries) are then optically combined before reaching the horizontal and vertical deflectors.

There are various methods of deflecting a laser beam in the horizontal and vertical axes. Deflection techniques include acousto-optic deflection and mechanical mirror deflection, which includes rotating polygon scanners, galvanometer mirrors, and hologon deflection.

Rotating polygon scanners with mirror facets are used when repetitive scan at a fixed rate is desired. A motor assembly rotates the polygon while the laser beam reflects off the mirrored facets (See Fig. 5). These motor assemblies operate at very high speeds. Turbine driven polygon motor

assemblies are available that operate at 1.2 million revolutions per minute (RPM). Polygon scan mirrors can be fabricated to specification. As the polygon rotates, the angle of incidence of the laser beam is changed, which in turn changes the angle of deflection, and the laser beam traces out one line for each facet. The polygon scanner is commonly used in laser raster projection displays to provide horizontal deflection.

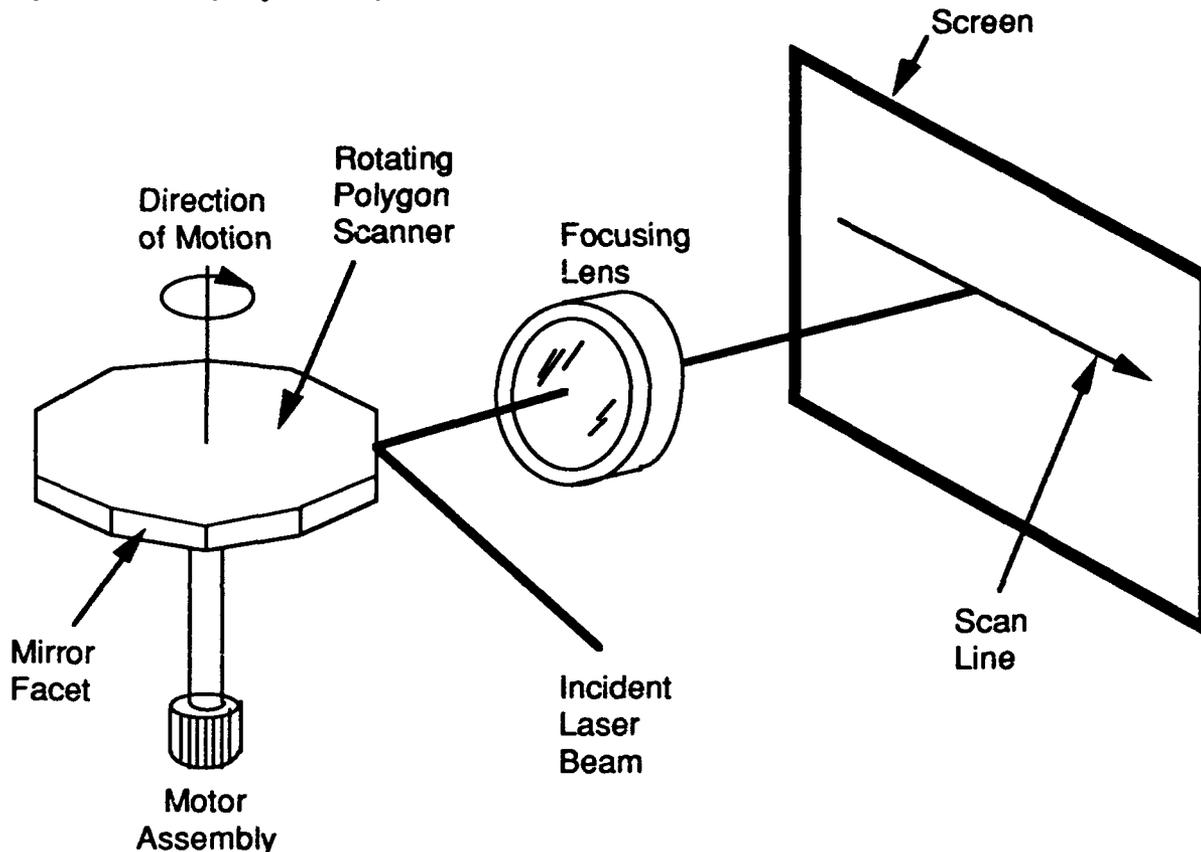


Figure 5
Rotating Polygon Laser Deflector

Polygon deflection rates depend on the RPM of the polygon and the number of facets on the polygon. To increase the number of scan lines, either the number of facets, the polygon rotational speed, or both can be increased.

Galvanometer deflectors are widely used as the vertical deflector in raster laser projection displays. A galvanometer provides single axis

rotation of a mirror, which in turn deflects the laser beam. Galvanometers capable of deflecting a 5,000-line scene at 60 Hz are available.

Acousto-optic deflectors work in a similar manner as the acousto-optic modulator. The difference is that acousto-optic deflectors vary acoustic drive frequency to deflect the beam where the acousto-optic modulator varies acoustic drive amplitude to modulate the beam. Acousto-optic deflection is commonly used for horizontal deflection of a raster laser display; however, this technique could be used for vertical deflection as well.

Laser displays are not without some problems. One of them is speckle. Speckle is a phenomena unique to laser-based displays. Speckle is the sparkling/granularity effect visible in laser images which comes from interference of the coherent laser beam with itself after passing through or reflecting off a diffuse screen. Speckle is present in most laser displays. It is noticed less at lower luminance and can become brilliant at higher luminances. Speckle removal techniques are available. Speckle can be removed by either removing the coherency of the light or by overlaying many different speckle patterns in space so they average out to be a smooth image (Welford and Winston, 1989).

The technology to construct a full-color, high-resolution laser projector is now becoming available. With the advent of laser diodes and solid-state lasers, and the availability of acousto-optic modulators, deflectors, and high-speed polygon mirror scanners, cost-effective laser projection can be attained. These new technologies and techniques will surely reduce the power and cooling requirements that have stymied laser projection in the past. Companies such as Lincoln Laser of Phoenix, Arizona have been developing and constructing scanners, galvanometers, and laser projection devices since 1974. It is obvious that the technology and techniques are available to make a major step up in flight simulation visual display capability. Some development may be required to do so, but the major pieces appear to be in place. Can we do it? Definitely!

Conclusions

Previous laser displays have been plagued by inefficiencies that required cumbersome power and cooling requirements. This has limited their success. New and rapidly advancing technologies and techniques promise to relieve many of the difficulties associated with previous laser projection systems. Efficient, low-cost, room temperature laser light sources are readily available. High-speed scanners and modulators have been available for some time. The technology to build a 2,000-line laser projector exists. With adequate development a 5,000-line projector is possible. Putting these components into an efficient, portable, highly capable laser projector will be the challenge.

Laser projection is a technology worth pursuing. Laser projection offers many benefits over current projection methods. Coherent laser light produces an increased color gamut, has the potential for much higher luminance, has zero persistence, and offers increased line rates. Laser projectors could project scenes in the IR spectrum and if required could provide noninterfering scenes in the same display for a pilot and weapon systems officer. These benefits would lead to major advances in flight simulation and training.

With current technology, pilots report visual acuity and target detail inferior to what is seen in the real world. Laser projection offers a visual scene that allows pilots to identify air and surface targets and their attitude with similar fidelity and realism as in the aircraft. The benefits from laser projection may also advance other display systems and stimulate emerging technologies, such as active holography, which require coherent laser light to produce images.

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