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The Laser Billboard

FEATURE ARTICLE

David Prutchi

A Low-Cost Laser Image Projection System

In Texas, there aren't many distractions for drivers, so billboards are priced skyhigh. David finds an alternative by developing his billboard using lasers. He gives some laser basics before walking us through the steps of how to build our own.



Southeast Texas roads are long and desolate. Driving for a few hours is so boring, we often find ourselves naming the cows.

"Hey, honey!" I'm often reminded, "Better not get too attached. Betsy there might end up as dinner some night."

Considering that only the infrequent sight of a bobbing oil pump tops cow-naming as a distraction, it's no surprise that roadside billboards in this area are so effective. Yet, when my wife recently tried leasing one to advertise a new hotel, they were next to impossible to find and ridiculously expensive.

It was time to bring high tech to the rescue. Let's see, where did I put my laser? We'll also need a large barn wall facing the road....

LASER PROJECTOR

Unlike the electron-beam raster

scanning method that reproduces TV images on the face of a CRT, laser-graphics projectors usually employ vector scanning. The laser beam is steered along the contour to be drawn to form a cartoon-like picture.

Vector scanning happens at the heart of a laser projector through the scanner assembly. Inside, two electro-mechanical galvanometers ("galvos") move small mirrors that steer the laser beam under computer control.

A galvo resembles a small DC motor with a restricted range of rotation (see Figure 1). A current flowing through the drive coil induces a magnetic field that interacts with the constant magnetic field of the pole-piece coil.

Torque created by the magnetic interaction causes the rotation of a small mirror affixed to the shaft of the galvo's moving armature. An impinging laser beam is then deflected along a line perpendicular to the mirror's axis of rotation. The laser dot's position on the image line depends on the current

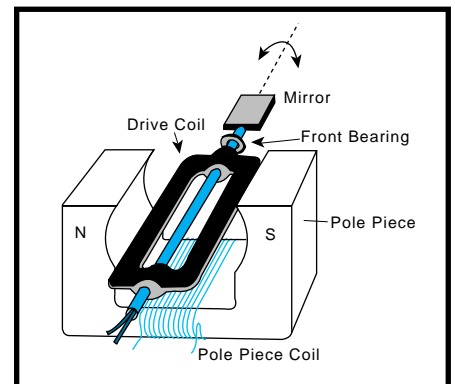


Figure 1—A galvo resembles a small DC motor with a very restricted range of rotation. The mirror affixed to the armature moves via magnetic repulsion or attraction between the drive coil and pole piece.

flowing through the drive coil.

Two galvos mounted orthogonally with respect to each other can position the laser dot anywhere on a 2D image plane. Scanning this dot at high speed forms the cartoon-like image.

In a CRT, a complete image is fully available for a brief instant because phosphor on the screen keeps glowing after the electron beam crosses over it.

But, laser-graphics image formation can't rely on the persistence of the projection screen. It relies solely on the limited temporal response of the human visual system. So, the projected image's quality depends highly on the speed with which the beam can be steered and retraced.

Unfortunately, the electromechanical deflection mechanism in a laser projector has a high inertia compared to the electromagnetic or electrostatic deflection used in CRTs. Inertia and other dynamic parameters make it increasingly difficult to accurately position a laser beam on the image plane as high-frequency components are introduced in the control signals.

Under these conditions, a laser projector's bandwidth is typically limited by the first uncontrolled mechanical resonance of the galvos. As a rule of thumb, laser-dot positioning as a function of drive current is repeatable only if the drive signal is bandwidth limited to below one-fifth of the first resonant frequency.

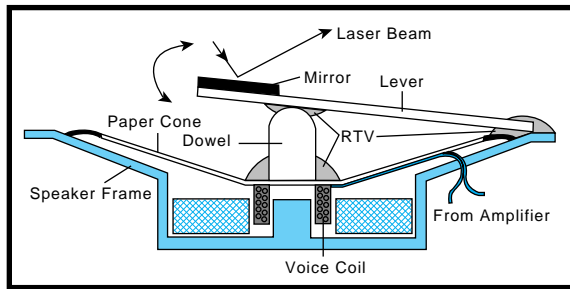


Figure 2—A crude galvo can be built from a speaker and a small mirror. Use RTV silicon adhesive to attach the PCB material lever to the speaker casing and to hold a wooden dowel between the paper cone and lever.

Despite efficient design and lightweight mirrors, a professional system's first resonance usually appears at 1–5 kHz. It's difficult to retrace a complex image slow enough not to generate drive components beyond a few hundred Hertz, yet fast enough for retinal image formation with minimal flicker.

High-end projectors employ closed-loop control to extend the system's useful bandwidth. Galvos with integral position sensors are used within a servo control loop.

Performance doesn't come cheap. Professional-grade galvos run at about \$500–800 per axis. (Recall that two are required for 2D scanning.)

An affordable alternative that will get your feet wet in laser graphics is a \$75 two-axis open-loop scanner sold by Meredith Instruments (see Photo 1).

With a first resonance at ~200 Hz, its performance cannot be remotely compared to its more expensive counterparts'. Still, it can be used as the basis for a laser-graphics system ca-

pable of projecting simple vector graphics and geometrical pattern animations.

There's one more alternative to computer-controlled laser graphics on a shoestring. As Figure 2 shows, you can build a crude galvo from a small speaker (e.g., 1 W) and lightweight mirror.

Construct the lever from a piece of PCB or prototyping board. Carefully glue a small wooden dowel to the center of the speaker's paper cone. Use RTV silicon adhesive to form the fulcrum and link the dowel tip to the lever.

For the two orthogonal galvos needed for 2D projection, you may find all the parts in your junkbox. But, due to this arrangement's extremely poor frequency response, don't expect to reproduce more than the crudest graphics and geometrical patterns.

GALVO AMPLIFIERS

The pole magnetic field in a galvo is usually established by energizing a coil with a DC current. The drive coil, on the other hand, is powered by a DC-coupled amplifier.

Driving a small open-loop servo is simple with widely available power op-amps. The pair of LM759s in Figure 3 provide up to 325 mA of drive current to each galvo.

The amplifiers are operated at unity gain from symmetrical ± 12 -V power supplies. A separate +12-V line powers the pole-piece coil.

Laser Safety

Even low-powered laser beams may cause irreversible damage if aimed directly at the human eye. Higher powered beams can start fires, burn flesh, ignite combustible materials, and cause permanent eye damage from even scattered reflections.

Therefore, a laser beam or its reflections should never be aimed at yourself or anyone else. Lasers and laser projectors should be used only by adults or with adult supervision. Although used for entertainment, a laser projector is not a toy. It must be used safely and responsibly.

Laser projectors and laser light shows are regulated by the federal government in addition to many state and local authorities. The Center for Devices and Radiological Health (CDRH) handles certification.

Laser projects often involve power supplies capable of producing severe electrical shock. Proper safety precautions

must be taken by the designer and builder to ensure proper handling, construction, and labeling of these supplies.

This laser-projector project is presented exclusively for informational purposes. The author does not make representations as to the completeness or accuracy of the information contained herein and disclaims any liability for damages or injury, whether caused by or arising from lack of completeness, inaccuracy of information, misinterpretation of directions, misapplication of circuits and information, or otherwise.

CDRH—Food and Drug Administration
U.S. Dept. of Health and Human Services
1390 Piccard Dr., HFZ-312
Rockville, MD 20850
(301) 427-1172

It's difficult to damage the LM759s, given their internal current limiting and thermal shutdown. However, they do run hot, so ample heat sinking is necessary.

Although galvo-amplifier design may look relatively straightforward using any suitable commercial power op-amp, a more complex design is needed once you decide to upgrade to professional-grade galvos. Driving the higher power units can be particularly challenging since they present a reactive load as well as reverse electromotive force (EMF) to the driving amplifier's output stage.

This EMF is generated when the drive signal works against the galvo's inductance and inertia, and it must be considered in the driver's design. In general, DC coupling into inductive loads is problematic because the current waveform lags the applied drive voltage, resulting in higher instantaneous and average power dissipation.

Interestingly, however, the same reverse EMF can be fed back to the driving amplifier to dampen unwanted oscillations and extend the usable galvo bandwidth. The coil drive voltage V_{drive} for a certain galvo may be expressed by:

$$V_{drive} = T \frac{d\theta}{dt} + L_{coil} \frac{di}{dt} + iR_{coil} \quad [1]$$

where T is the torque constant, a galvo parameter (expressed in Nm/A) that describes how much torque is produced on the rotor assembly by each ampere of current i flowing through the drive coil.

The absolute angular position of the rotor assembly at any time t is expressed by θ . L_{coil} and R_{coil} are the inductance and resistance of the drive coil, respectively.

Considering that the torque should ultimately equal the inertial resistance of the rotor and mirror, oscillations may be dampened by tailoring the system's transfer function as shown in Figure 4. Here, I included the measurable terms of equation 1 within the output amplifier's feedback path.

The instantaneous current through the drive coil i is converted to a corresponding voltage signal by the current sense resistor:

$$R_{sense} = 1\Omega$$

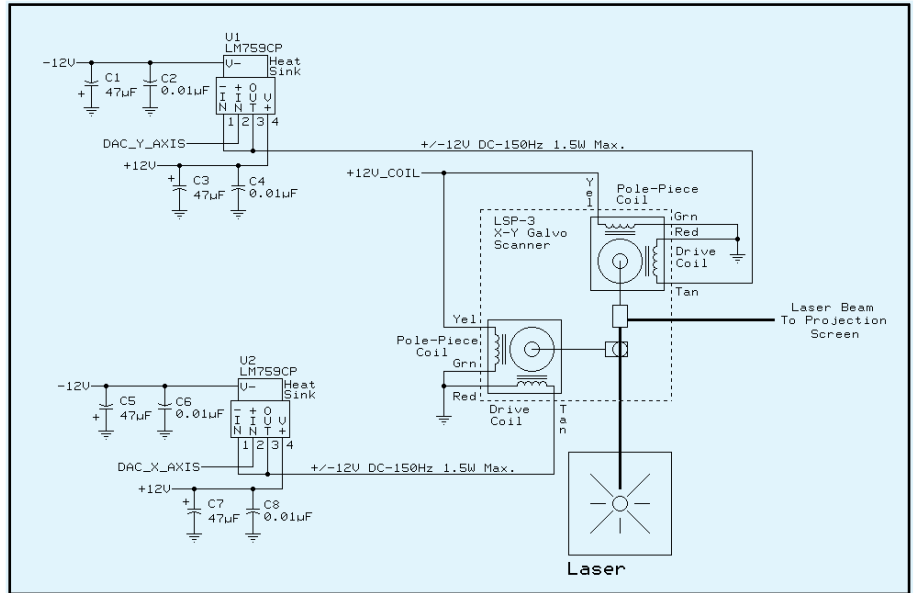


Figure 3—Low-cost power op-amps can drive the galvos of the two-axis scanner. Currents flowing through the drive coils induce magnetic fields that interact with the constant magnetic field generated by the pole-piece coil in each galvo. The laser beam is deflected in each axis proportionately to the drive voltage applied to the respective power op-amp.

The resistors and capacitors on the input and feedback paths of A3 differentiate this signal and simulate the effect of such current variation on an RC equivalent of the coil's inductance.

To do so, the equivalent resistance R_{eq} and the equivalent capacitor C_{eq} are chosen such that:

$$L_{coil} = R_{eq} C_{eq} \quad [2]$$

A3's output approximates the term $L \frac{di}{dt}$ of equation 1. At the same time, the instantaneous voltage across the coil is sampled by op-amp A2, providing a measurement of V_{drive} .

Extending this control concept, closed-loop galvos have an integral position sensor to provide position feedback signals to a servo amplifier. It's easy to understand, then, that servo

amplifiers for closed-loop scanning take full advantage of equation 1 by providing an actual measurement of the angular position θ to a suitable transfer function relating position to the drive current [1].

Due to their low inertia, capacitive sensors have been the most popular position detectors in closed-loop galvos. The servo controller is typically implemented by an analog circuit that places the position sensor within the amplifier's feedback path.

In general, the servo system is designed with a bandwidth broad enough to reject dynamic disturbances to the galvo's position, such that the scanner's output closely reproduces the control input signal.

As well, notch filters at the galvo's resonances are often used on the control

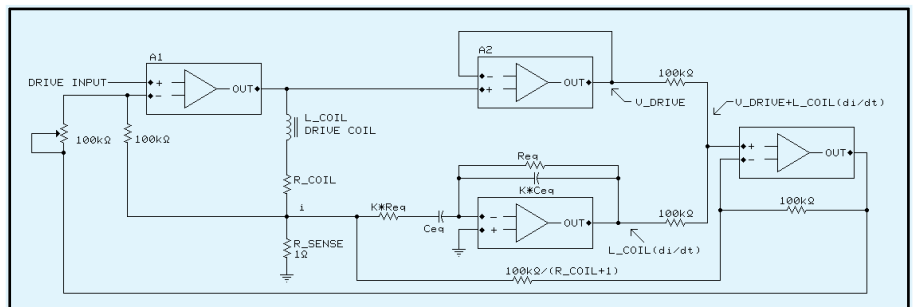


Figure 4—Oscillations may be dampened by tailoring the galvo system's transfer function. The measurable terms of transfer function can be included within the feedback path of the output amplifier. The components on the input and feedback paths of A3 differentiate the current through the coil to simulate current variation on the coil's inductance. A3's output approximates $L \frac{di}{dt}$, and the instantaneous voltage across the coil is sampled by A2. These signals combine to dampen the galvo at critical operating points.

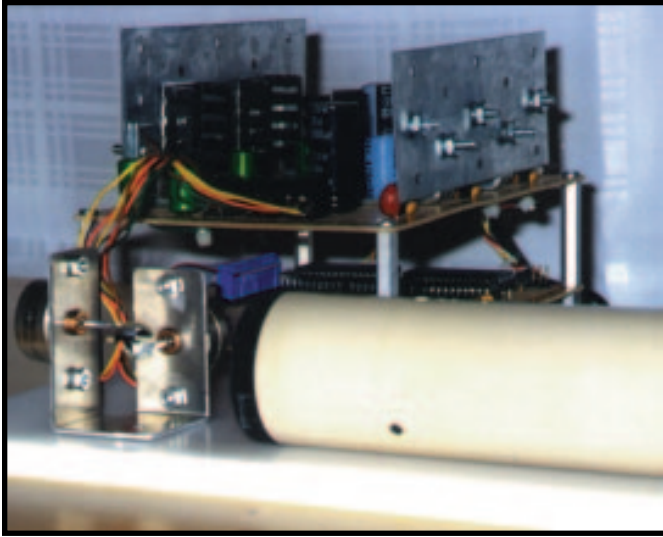


Photo 1—A simple computer-controlled laser graphics projector can be built around an inexpensive two-axis open-loop scanner. The top circuit board comprises the power op-amps that drive the scanner's galvos, as well as the power-supply components. The lower circuit board has two 12-bit DACs and an interface connecting to the PC printer port.

signal input path. This technique makes it possible to extend the servo's control bandwidth by skipping over problematic phase crossover frequencies.

A discussion on the theoretical background required for designing closed-loop control circuits is beyond the scope of this article, but you should have no problem finding good references with varying degrees of sophistication [2].

PROJECTOR CONTROL

Driving the galvo amplifiers of the low-cost laser projector requires playing the image's vector coordinates through two DACs into the amplifier inputs. The circuit of Figure 5 enables the PC to drive two Analog Devices AD667 (or Maxim MAX667) 12-bit DACs from the parallel printer port.

The DACs receive data from three 8-bit latches. The printer port presents the required 24 bits of data as three sequential 8-bit words which are demultiplexed by the three 74LS374 latches.

U4 holds the four least significant bits of each DAC. U3 holds the 8 most significant bits of the x-channel DAC, while U5 holds those of the y-channel DAC.

If desired, 8-bit operation can be selected through J2. Once the 24-bit information defining a coordinate pair is available at the outputs of U3–U5, the DAC outputs are simultaneously updated by strobing pin 16 of the printer port.

Power is obtained from the circuit shown in Figure 6. Current from a 1-A

12-VAC transformer is rectified and regulated to ± 12 V for the DACs and galvo amplifiers. A separate +12-V regulator powers the pole-piece coils of the galvos. In addition, +5 V is generated to supply the 74LS374 latches.

USING VECTOR GRAPHICS

LASER.BAS, a Quick BASIC program, is used to draw vector graphics that can then be displayed by the laser projector. The vector-graphics drawing tablet is controlled through the cursor-movement keys (i.e., keyboard arrows or numeric keypad).

The spacebar is used to toggle on and off the line to be traced by the laser. Coordinates of points that appear red onscreen are stored in a vector-image file, while green points are disregarded.

To draw a figure, take the cursor to the desired initial point using a green line (tracing off) and toggle on the saving of coordinates (red tracing). Draw the image point by point, turning the tracing off as necessary.

Keep in mind, however, that this laser projector has no retrace blanking. As such, a line is generated between successively traced segments.

You'll soon notice it's not easy to draw just by attempting to trace over an imaginary cartoon of the desired figure. It's much easier to first draw the figure on a transparent film (e.g., the transparencies used for overhead projection), overlay it on the computer screen, and trace the figure with the cursor keys.

By keeping the flow of the figure as smooth as possible, with generous

curves and few discontinuities, you will band limit the drive signals and hopefully not excite undesirable resonances. If you plan to project letters or words, use smooth cursive writing and add an artistic return path for the retrace beam connecting the first and last points.

Projection is accomplished by writing the stored coordinates in an endless loop. Since the writing speed to the DACs is highly dependent on system factors (e.g., CPU clock speed, OS shell, and Quick BASIC compiler version), you'll need to tweak the program's operation to achieve proper results.

The program includes code to skip over unnecessary coordinate points, as well as introduce delay loops between successive write operations to the DACs. In general, keep the writing speed sufficiently low to obtain good beam steering, yet high enough to generate a flicker-free image.

This software is intended only as an example of implementing an open-loop vector-graphics control program. Major enhancements could be made to it.

First of all, an FFT-based spectral-analysis routine (see "Spectral Analysis: FFTs and Beyond," *INK* 52) could help analyze the beam's path and look for frequency components which could trigger unwanted resonances in the galvos.

A suitable algorithm could then smooth over the hard transitions to limit their spectral content to a level the galvos can handle. Or, the signal can be notch filtered to skip over the resonance frequencies to gain bandwidth.

Other interesting improvements can be implemented through software. For example, if a mechanical resonator is driven with a stair-step function consisting of an intermediate level approximately halfway between the initial and final drive values with a duration equal to half the period of the resonator, overshoot and ringing are suppressed.

As such, the inertial load tends to arrive to the final rest position at zero velocity with a total time of one-half the resonance period for the move.

You may also add a more powerful graphics editor that enables freehand drawing using a mouse or light pen, fancy graphic and animation routines,

and a nice Windows-based GUI. If you write such software, please share it with the rest of us.

ANIMATED GEOMETRIC PATTERNS

It's not always necessary to manually enter a figure for display. Interesting graphics can be synthesized using mathematical functions. Rotating "spiro-graph" patterns are easy to generate and display using the laser projector.

These patterns are created by driving the *x*- and *y*-axes with continuous sinusoidal signals of different frequency, amplitude, and phase. Since the frequency content of these signals is limited and no discontinuities exist in the signal or its derivatives, even rudimentary galvos like those in Figure 2 can project these patterns with good performance.

In LASER.BAS, Lissajous patterns are generated by driving the *x*-axis galvo with a sinusoidal frequency ω_1 while driving the *y*-axis with an quadrature sinusoidal of frequency ω_2 .

The ratio between ω_1 and ω_2 determines the number of peaks in the Lissajous pattern. Introduce rotation by slightly increasing the phase difference between the signals each time a complete pattern is traced.

Polar roses are generated by not only feeding the *x*- and *y*-axis with quadrature signals, but by also varying the amplitude of the sinusoidal components with another sinusoidal function. The number of loops in the polar rose is given by the frequency of this third sinusoidal component.

Complexity can be taken one step further by making the driving function for each galvo contain various sinusoidal components of varying phase and amplitude. One result is to generate collapsing spirals that give the illusion of a rotating black hole.

Go ahead. Dig out your old trigonometry and analytic geometry books and keep on playing!

LASERS

Of course, an indispensable part of a laser projector is the laser. And, almost any visible kind can be used for display.

Low-powered (5–10 mW) Helium-Neon (HeNe) lasers are suitable for indoor and limited exterior light shows. They're inexpensive—surplus units can be found for as little as \$35.

Typical HeNe lasers produce red light at 633 nm, but green (543 nm), yellow (594 nm), and orange (612 nm)

ones are now available, albeit at higher prices than their red counterparts. For a few thousand dollars, high-power (30–50 mW) versions are also available for serious light-show displays.

Another low-cost alternative is to use a visible laser diode. Since it's not usually possible to effectively drive a laser diode at room temperature from a DC source, laser diodes are available with a photodiode used for driving control. The photodiode yields a signal that automatically controls the laser diode's power output as a function of the current delivered by the driver circuit.

Diode lasers can also be found as part of modules that include a diode, driver, beam-collating optics, and case that operates as a heat sink. Battery-operated pencil-like laser modules are widely sold as laser pointers.

In any case, these modules require only a DC power source and typically produce red beams at either 670 or 635 nm. If possible, select the 635-nm wavelength, since at the same power, it's four times brighter to the human eye than the 670-nm wavelength. Because of their reduced power (3–5 mW), however, diode lasers are suitable only for indoor and studio work.

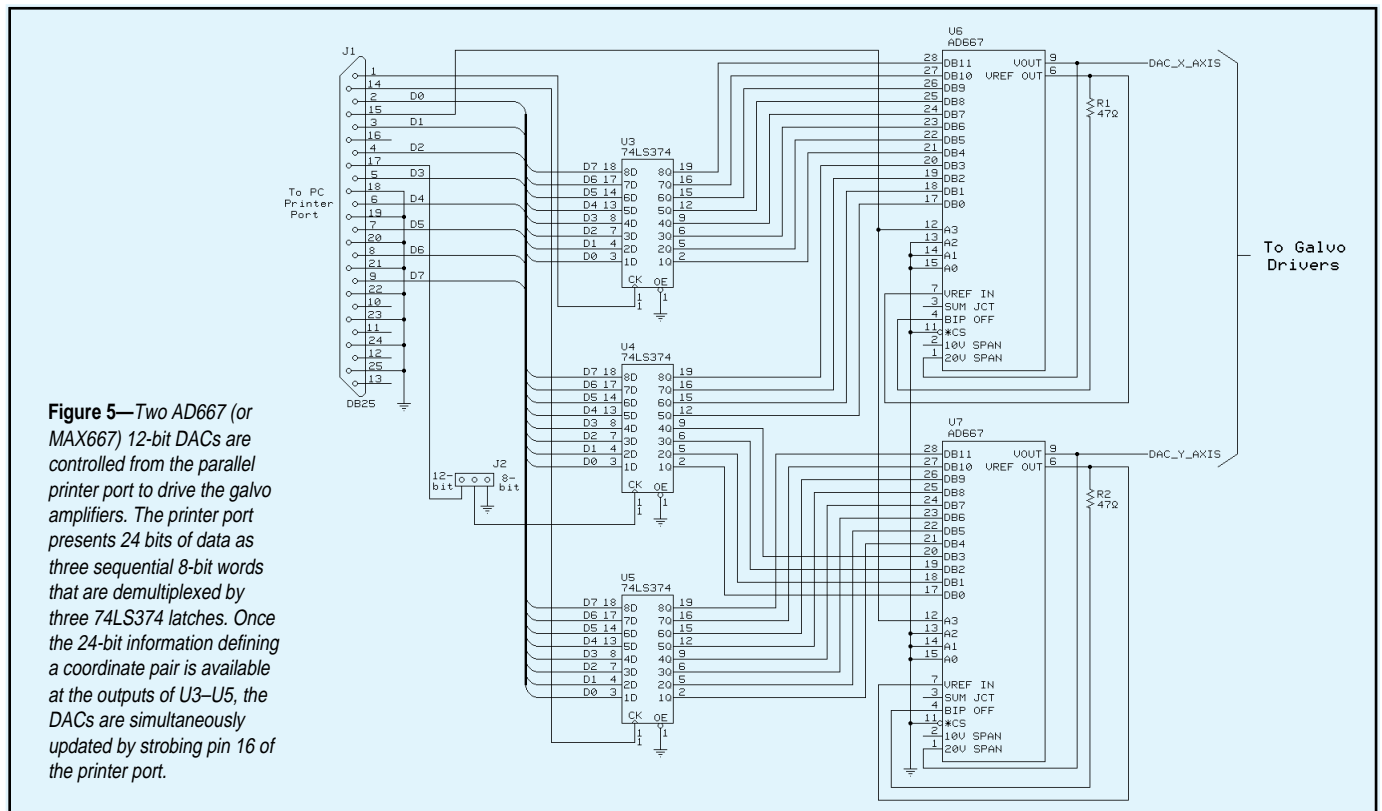


Figure 5—Two AD667 (or MAX667) 12-bit DACs are controlled from the parallel printer port to drive the galvo amplifiers. The printer port presents 24 bits of data as three sequential 8-bit words that are demultiplexed by three 74LS374 latches. Once the 24-bit information defining a coordinate pair is available at the outputs of U3–U5, the DACs are simultaneously updated by strobing pin 16 of the printer port.

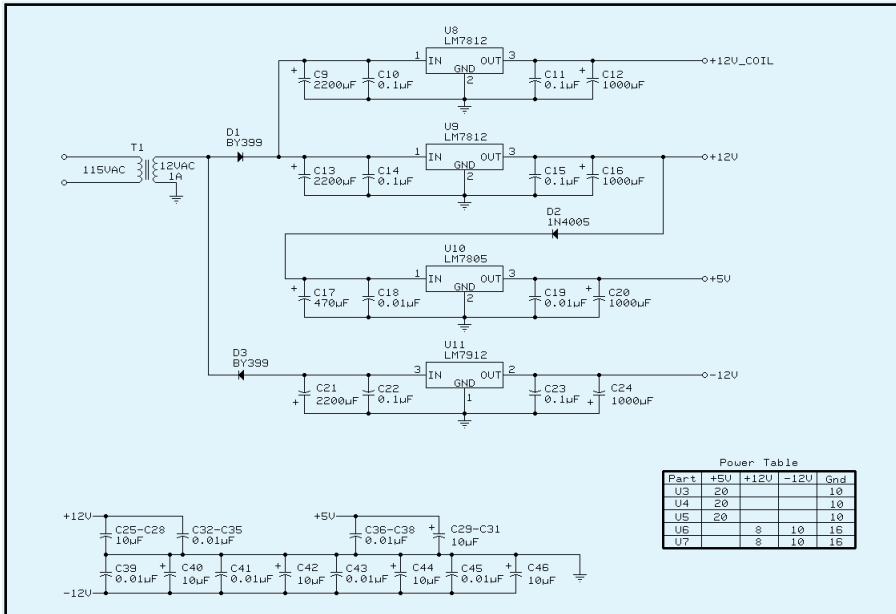


Figure 6—The projector is powered by a 12-VAC wall transformer. The circuit uses linear regulators to produce ± 12 V for the DACs and galvo amplifiers, +12 V to power the galvos' pole-piece coils, and +5 V to supply the 74LS374 latches.

For outdoor graphics, argon or mixed-gas argon/krypton (green-blue or red-yellow-green-blue) do the best job. Medium-power lasers (30–100 mW) can handle most indoor graphics as well as indoor beam effects.

Events in which beams must be visible under adverse conditions (e.g., outdoor shows in high-brightness areas) usually demand water-cooled lasers with optical power outputs that often reach 5 W!

Regardless of the laser you select, please keep safety in mind at all times (see sidebar, "Laser Safety"). Never aim a laser beam or its reflections at yourself or anyone else, and always use appropriate safety eyewear [3].

THE BIG PICTURE

Recently, a sports commentator on NPR complained that today's basketball games are perceived as necessary disturbances in between the pregame and intermission laser shows.

Despite his exaggeration, laser shows seem to be everywhere these days—from small tradeshow booths to the Olympic Games. Their frequent use is mostly due to the advanced technology that has emerged in the last few years.

Galvo writing speeds in high-end professional projectors are now in the 30,000-points/s range, and acousto-optic modulators can create full-color images from "whitelight" laser sources. In

addition to the vector graphics that can now be created, modern laser projectors can display full-color raster graphics.

These images are not VGA-quality, since the achieved resolution is only about 50 pixels \times 50 lines. But, through image-processing magic, subtly shaded photos can be scanned and projected in a fraction of the time it takes an artist to draw a vector-graphics cartoon [4].

Well, using the laser to project an ad on the old barn along the highway might not be such a good idea after all. But, I'm sure to make the other dads jealous when my kid's birthday party is preceded by a cool laser-show. 📌

David Prutchi has a Ph.D. in Biomedical Engineering from Tel-Aviv University. He is a staff engineer at Sulzer-Intermedics, and his main R&D interest is biomedical signal processing in implantable devices. You may reach him at adnav@tgn.net.

SOFTWARE

The LASER.BAS Quick BASIC source code for this article can be found on the Circuit Cellar Web site along with LOVE.DAT and MOUSE2.DAT, demo graphics for the project, and SOURCES.TXT, additional sources for laser equipment.

REFERENCES

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- [2] F.P. Tedeschi, *How to Design, Build, & Use Electronic Control Systems*, TAB Books, Blue Ridge Summit, PA, 1981.
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- [4] P. Murphy, "Software Stretches Laser Artists' Imagination," *Laser Focus World*, **32:12**, 148–150, 1996.

SOURCES

AD667

Analog Devices
One Technology Way
Norwood, MA 02062-9106
(617) 329-4700
Fax: (617) 329-1241

Galvo assembly (LSP-3)

Meredith Instruments
5420 W. Camelback, Ste. 4
Glendale, AZ 85301
(602) 934-9387
Fax: (602) 934-9482

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