Open-Source Laser

ME235 Final Report

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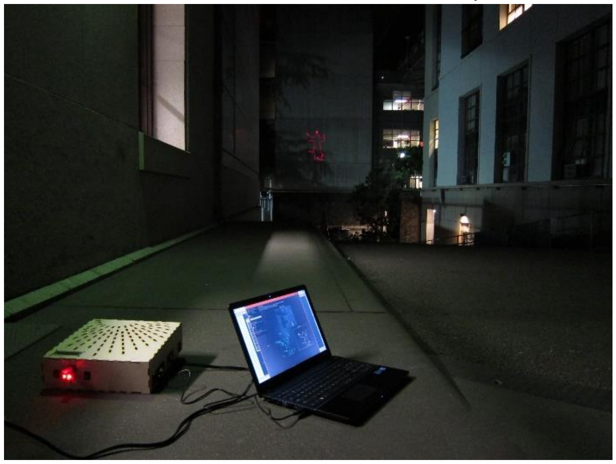

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Background and Motivation

The goal of this project was to develop an open-source, low-cost laser project capable of projecting industry standard ILDA (International Laser Display Association) image files. Laser projectors are typically used for theatrical and stage lighting to project vector graphics or produce lighting effects. Since laser projectors use a collimated light source that does not defocus or lose intensity with distance, they are perfectly suited for long range projection applications that would otherwise require very large and expensive long throw projectors. As an example, a low-cost laser projector could be used to projection bomb buildings with text and motion graphics for mass communication during public demonstrations. Developing an open-source, low-cost alternative to existing projection bombing methods has the potential to expand people's ability to reclaim public space and mass communicate ideas.

Our projector operates by redirecting the path of a laser beam using mirrors mounted on galvanometers to trace out thousands of points per second, creating a cohesively projected image. The system executes closed loop at 20 kHz and operates using multiple interrupts, necessitating real time and multitasking programming.

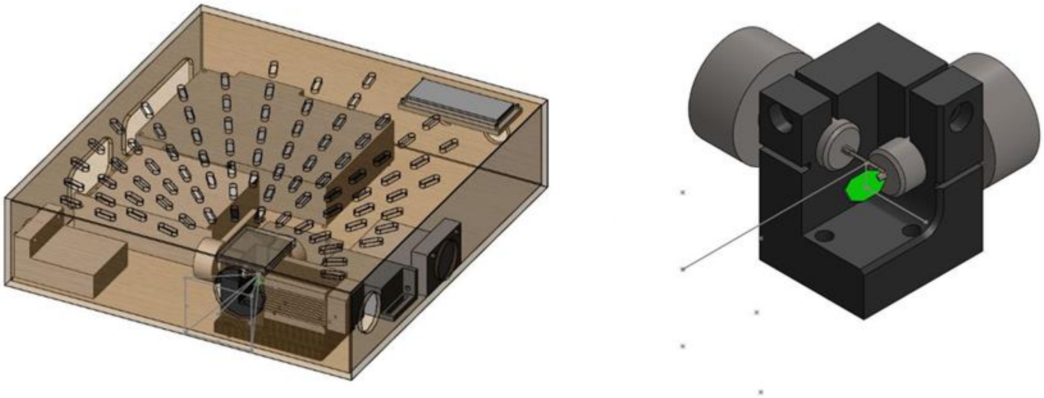


Figure 1Main laser projector assembly and close-up of mirror galvanometer assembly. The grey line on the mirror assembly represents the simulated laser path, redirected to display on a projection plane.

This document provides a summary of the achievements project and outlines improvements to be made for the second iteration.

Design Phase: Expected Technical Challenges

Projector Hardware

During the conceptual design phase of this project, challenges were anticipated in the fabrication and assembly of the mirror ensemble. The original plan was to fabricate a 360-faceted mirror assembly to controllably reflect the laser beam in the x and y directions. The mirror would rotate at extremely high speeds to achieve the 30 frames per second (the limit of detection perceivable by the human eye). However, this mirror assembly design would require high precision machining of the substrate material and placement of hundreds of millimeter-scale mirrors.

The alternative option was using a galvanometer system. A galvanometer is an electromechanical actuator that produces a rotary deflection when an electromagnetic field is generated. Mirror galvanometers are specialized galvanometers that are designed to precisely actuate small mirrors attached to the rotary shaft outputs at very high frequencies. A single mirror galvanometer can deflect a laser beam along one axis, therefore two galvanometers are necessary to achieve controlled manipulation in both the x and y direction. Initially, we were concerned about the feasibility of this option due to the high cost of most American made galvanometers (ranging on the order of hundreds to thousands of dollars) and the long lead time (on the order of 4-6 weeks) and unreliable quality of cheaper Chinese products. Fortunately, we were able to find a suitable option at a relatively low cost ($120) from a semi-reputable supplier on EBay.

Even though the two mirror galvanometer system reduced the necessary manufacturing precision, the team expected to have trouble precisely calibrating and aligning the mirror galvanometers with the laser beam path. Care was taken in design of the mirror bracket to allow for precision alignment.

Software: Embedded Design

During the design phase, various embedded solutions and software tools chains were evaluated, primarily the National Instruments SB-RIO with LabVIEW, and the Cypress PSoC.

The primary design challenge for the embedded system included multiplexing and synchronizing the control of the 2 galvanometers and the laser at extremely high speed. The required update frequency of the embedded system was calculated to be >20 kHz based on the laser projection specifications. The embedded system would also need two Digital to Analog Converters (DAC) to generate the analog signal required to control the mirror galvanometers.

The SB-Rio is not capable of analog output, and would have required external DACs. The SB-Rio would also have required LabVIEW to be used on the PC client side (not open source). In addition, the SB-Rio is FPGA based, which enables very high speed multi-task execution but at the cost of increasing development time (very long compile time). In comparison, the Cypress PSoC 5LP met the embedded system design requirements and could accommodate a number of PC communication protocols. When this was considered along with the PSoC's price point and free toolchain, it was determined that the PSoC better aligned it with the low-cost and open-source design philosophy of the project.

Current Project Status and Achievements

Overview

The system was successfully able to project images, both manually entered points and those read from an ILDA file. Interpolation mode successfully smoothed these images to increase the quality of the image. It effortlessly projected an image 30 yards onto a building, demonstrating its capability for mass communication. In computer vision mode, the system was able to dynamically track and project contours of people and objects in front of the camera, even projecting multiple contours. For example, when a team member juggled in front of the camera, his outline and the outline of each thrown ball were dynamically projected. This interactive feature added an entirely new dimension to what is possible with the developed system. The addition of a compact case and intuitive user interface make this open source laser projector easy and ready to use.

Figure 2 Operational laser projector system easily projects a camera vision captured image in low light at a distance.

Hardware

The laser system consists of:

1. Laser

   A high powered 150 mW red (650-660 nm wavelength) laser was chosen for long-distance laser projection. The laser requires a 12V DC power supply. The on/off state of the laser is controlled with a TTL signal that can be modulated up to a speed of 25 kHz.

2. Galvanometers (2)

   Two 20 kpps galvanometer scanning systems were used to reflect the laser beam in the x and y directions onto a projection plane. The galvanometer scanning system requires an 18V power supply. The position of the mirrors is controlled by a -5V to +5V analog input signal. At this voltage range, the maximum angle of deflection achieved with each galvanometer is 20 degrees. The range of the galvanometers can be further increased to 40 degrees in response to the same +/- 5V signal by adjusting the turnposts that are located on the driver boards of the galvanometers. Adjusting these potentiometers adjusts the sensitivity of the galvanometers, the maximum of which is 40 degrees at +/- 5V.

3. 3D Printed Bracket

   A 3D printed bracket was designed to hold the laser and galvanometers in precise alignment with each other. The uPrint FDM printer was used for rapid prototyping of this design. The laser is mounted as close to the first mirror (x-control) in effort to keep the reflected beam as small as possible - ensuring the beam is not at risk of falling off the edge of the mirror during the expected galvanometer range. Because the laser output is 150mW it is important to make sure the laser is never accidentally aimed at a person while energized. To mitigate uncontrolled laser trajectories a lid was built to enclose the top and sides of the galvanometer/laser assembly that were not intended for the laser exit. A second revision of the galvanometer/laser bracket should include this enclosing housing to further perfect the design.

4. Voltage source

   The voltage power source converts the 120V wall power to +/-18V DC power at 1A each. This voltage source was included in the galvanometer package. Although the initial data sheet called for a +/-24V DC power supply, the manufacturer assured us that +/-18V would be adequate, stating that +/-18V was, “same same”.

5. Printed circuit board to convert 18V power source to 12V and +/-5V power rails

   The printed circuit board accomplishes 2 functions. First, it converts +/-18V power rail supplied by the voltage source to 12V (to power laser) and +/-5V (to power differential op amps). Secondly, a differential op amp circuit is used to convert the single-ended output signal from the PSOC to a differential signal to increase the range of motion that the galvanometers can operate in. The printed circuit board was designed using Diptrace software and fabricated using a Board Mill.

6. PSoC to control galvanometer and laser assembly

   Three dimensional data is streamed from the processing computer to the PSoC to be interpreted and converted to analog signals that are recognizable by the galvanometers and laser. These data elements are X coordinates, Y coordinates, and Laser state (on/off). The PSoC converts these digital signals to analog signals via the onboard 8bit DAC.

7. Laser cut enclosure

An enclosure was designed using SolidWorks to house all of the above components. Mounting holes, power inlet, laser outlet, and heat venting holes were all designated by patterning within SolidWorks. This patterning was exported as a vector file and overlaid on a key-joint enclosure pattern that was created at makercase.com. The enclosure was laser cut out of ¼" plywood and assembled using wood adhesive.

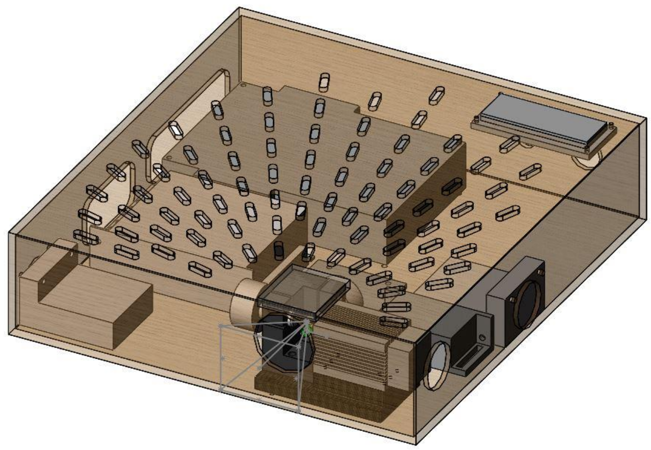


Figure 3 CAD model of completed projector, including laser-cut wooden box design.

Software

Overview: Data and Control Flow

The main structure of the software involves communication between the computer, PSoC, and laser/galvanometer system (see Figure 4). After extracting coordinates from a data source selected by the user through the user interface (ILDA file, camera feed, cursor position), the PC streams the appropriate control signals via USB to the PSoC buffer using a UART protocol. Every 200 µs, a polling interrupt transfers the data from the buffer to the non-interpolated data array. Meanwhile, in the main loop, interpolated points are being calculated between each of the 'raw' points in the non-interpolated data array. Interpolation smooths (Figure 5) the operation of the galvanometers and helps to reduce 'hot spots' in the projected image (where the laser point dwells). These new points are then stored in an interpolated data array. Every 25µs, a laser firing interrupt is called, ensuring that the laser is operating at the maximum points per second (20kpps in our case). This sends the signals to the laser galvanometers using a DAC. Which data array the laser interrupt pulls coordinates from is based on whether the Boolean for interpolation is true or false (controlled by a switch). Figure 6 demonstrates the time scale of each function.

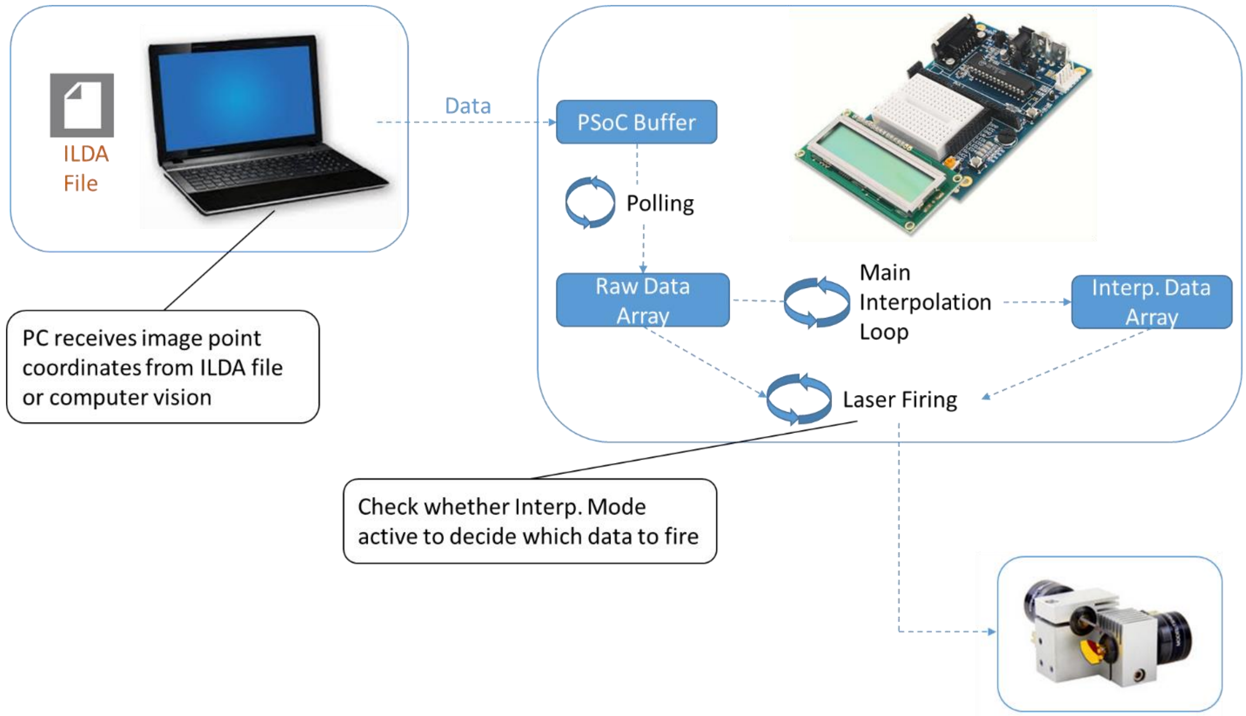


Figure 4 Schematic showing data flow between the PC, PSoC, and laser system.

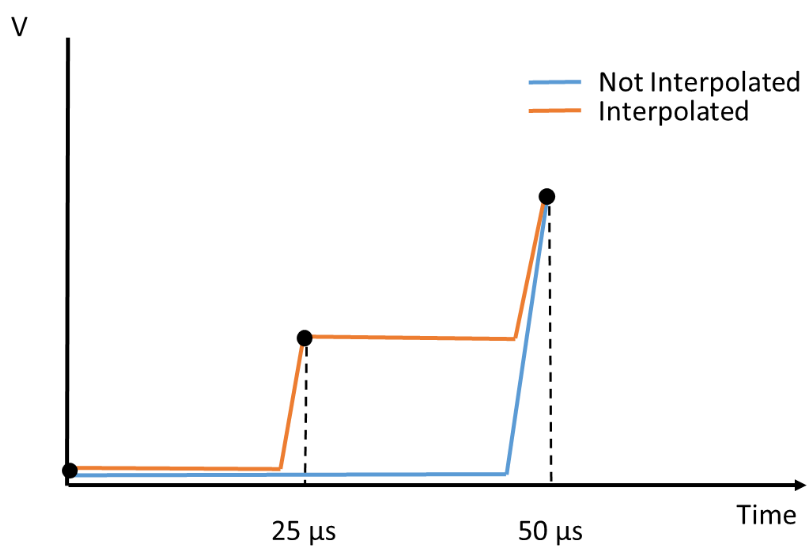


Figure 5 Demonstrates the 'smoothing' action of interpolation, as the laser receives an intermediate voltage step between its original and final voltage value (original and final coordinate location).

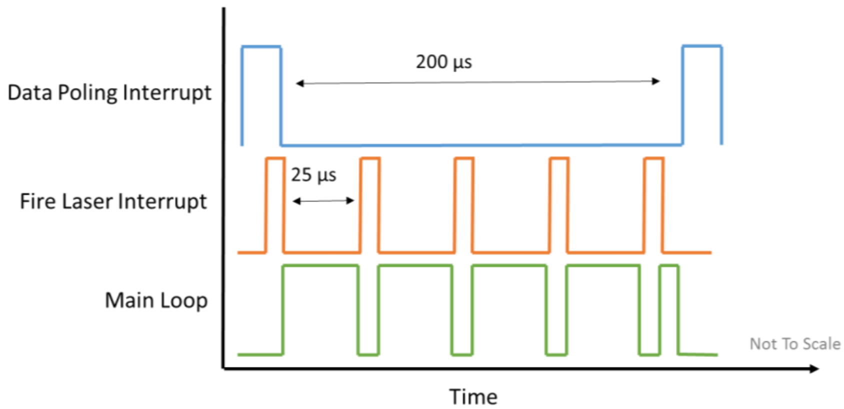


Figure 6 A demonstration of the timing of each multitasking element. Note figure not to scale.

A custom user interface was designed using openFrameworks libraries that features many different modes and functionalities. Instructions are included on the interface, and intuitive controls allow a user to quickly become familiar with laser operation. Manual mode allows for manual selection of laser projection point coordinates, useful for testing the size of the projection plane. ILDA mode allows the import and projection of images from ILDA files, with easy cycling through loaded images. Computer vision mode utilizes blob detection to dynamically project silhouettes from a laptop camera.

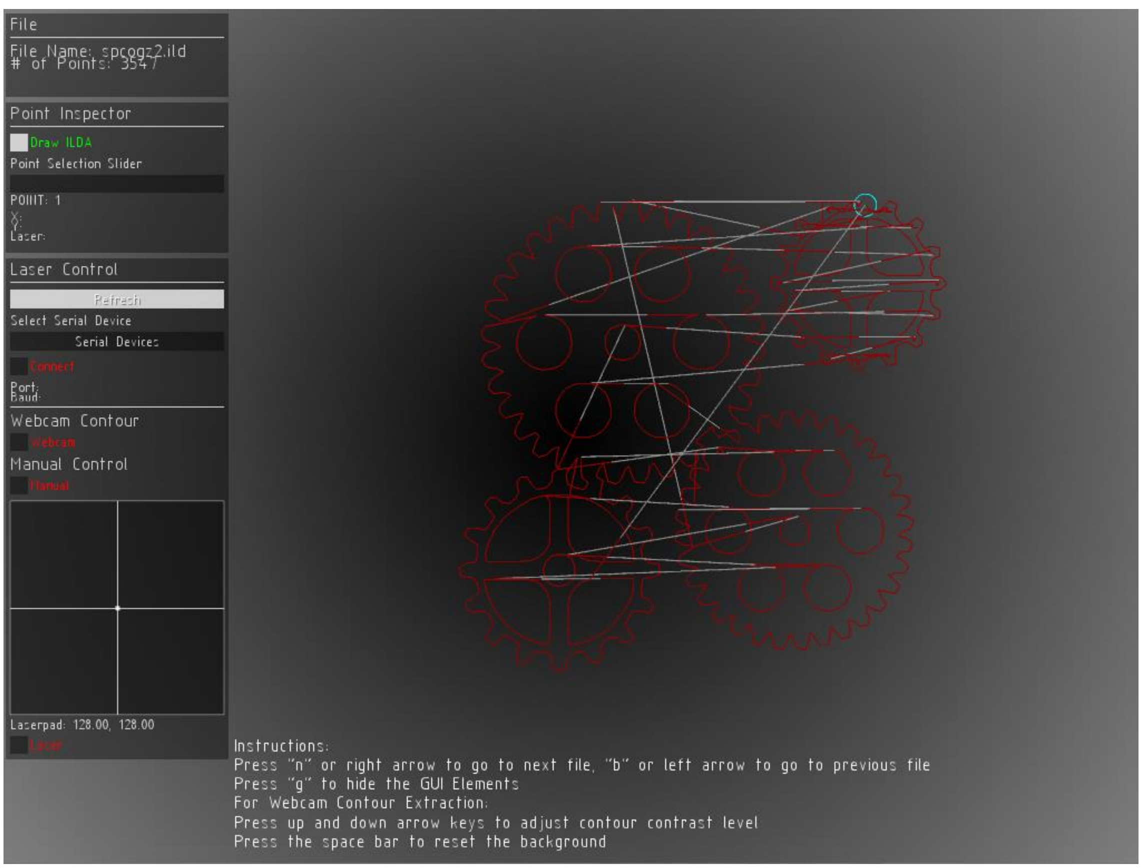


Figure 7 Screenshot from GUI. The interface displays not only the image to be displayed (red), but laser traces inbetween, where the laser is off, to move between contours.

PC Software

The PC client software needed to provide an intuitive GUI interface for the user, and conduct the core data processing. To this end, openFrameworks was chosen as a platform to develop an intuitive GUI. openFrameworks is an open-source C++ toolkit originally designed for creative coding, but has grown as a popular development tool for a vast array of projects.

The C++ code we developed relies on the standard openFrameworks libraries (e.g. math, sound, video, graphics), and add-on libraries (e.g. Camera Vision, XML settings, advanced UI), all of which can be download for free. The openFrameworks homepage provides helpful tutorials for understanding its many features, but at its core there are (a) program flow functions such as setup(), update(), draw(), and (b) event handling functions such as keyPressed(), mouseMoved(), mousePressed(), etc.

The setup function is called when the program first launches, typically initializing features like window size and font size. After the setup function runs, the update and draw functions begin a loop that continues until your program ends. Update handles any data processing, and draw outputs graphics to the monitor.

The PC code written for this project is contained in five files, main.c, testApp.h testApp.c, ilda_processing.c, and gui_features.c. The first two files are generated when creating an openFrameworks projects, and allows the program to access functionality from the openFrameworks libraries. The testApp.c file contains the code for the setup, update, and draw functions. As the names imply, ilda_processing.c file handles the reading and processing of ILDA files, and the gui_features.c file handles any interactions with widgets and toggles on the GUI. The files are thoroughly documented; each command or logical unit of commands is commented to preserve readability for any future development. The program be compiled from source, independent of OS platform.

PSoC Software

On the embedded side of the project, the PSoC handled data communication over USBUART with the PC, interpolation of the points, and simultaneously generating the control signals for the mirror galvanometers and the laser with two DACs and a digital pin. The PSoC 5LP has a 32-bit ARM cortex -m3 CPU combined with programmable mixed-signal blocks. The programmable blocks enabled us to easily configure all the components we needed by dragging and dropping in the desired component blocks and wiring them diagrammatically (Figure 8). We utilized analog signal components (DAC, op amps), and digital signal components (USBUART, timers, interrupts). The PSoC 5LP development board we used also had a LCD screen which was immensely helpful in debugging our communication protocol and interrupt logic.

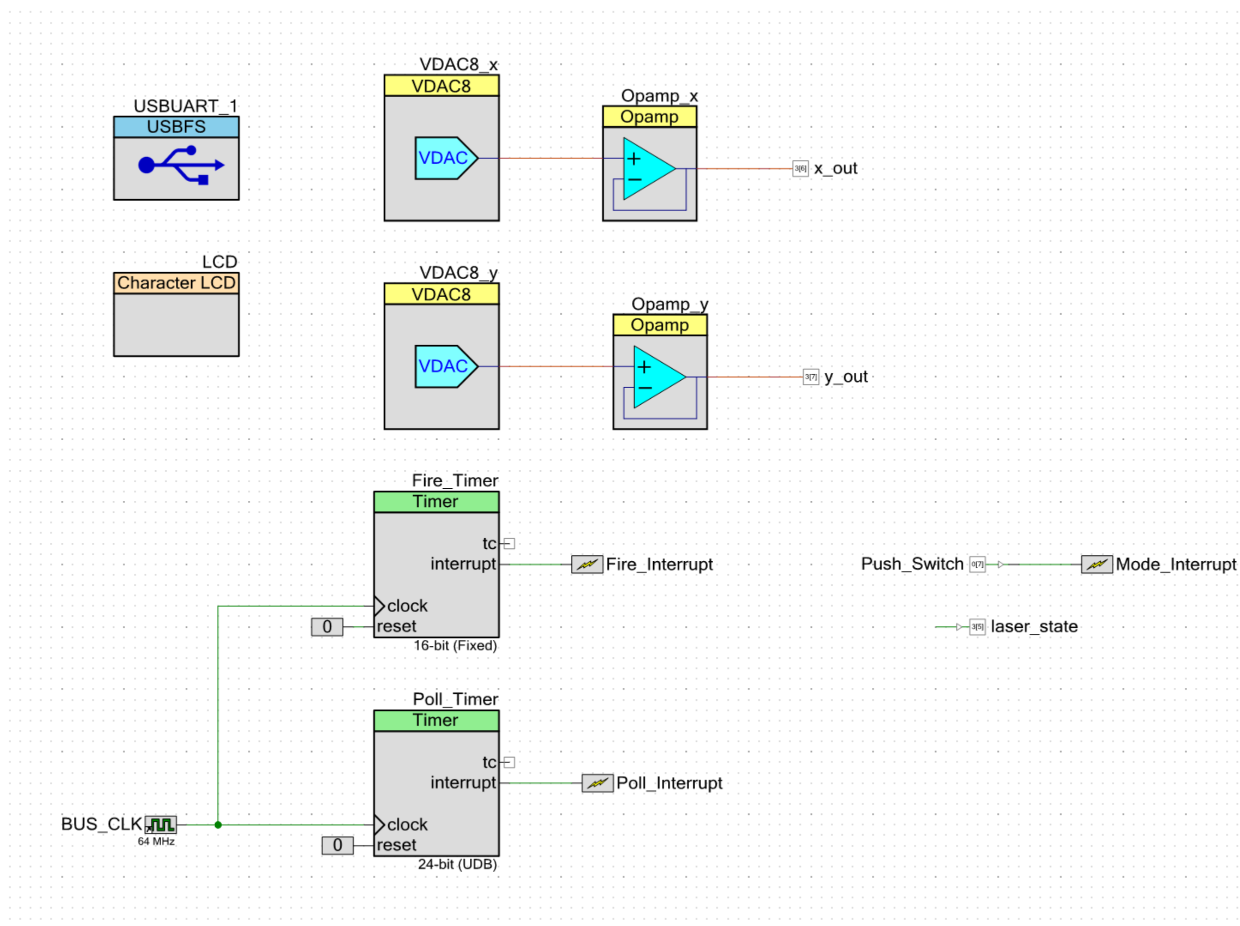


Figure 8 PSoC block diagram.

Three interrupts are used in our block design including two timer interrupts named Fire_Timer and Poll_Timer, and a Mode_Interrupt that was trigger by a momentary push button. Fire_Timer fires every 50us outputting the two control signals to the galvanometers through two 8-bit DACs as well as a digital TTL level signal to the laser driver. Poll_Timer triggers every 200us, checking if the UART buffer is filled with a new packet, and if so, grabs the coordinate data and stores them in arrays. Finally, Mode_Interrupt is set to trigger by the rising edge of the Push_Switch signal, which enables the user to select between the raw five coordinate or interpolated nine coordinate firing modes.

The main loop of the microprocessor handles interpolating four additional points based on each new five coordinate packet received from the UART buffer. It also handles the LCD display logic and output. All of the PSoC code was written in C.

Key Development Challenges

Hardware

The design for the differential op amp circuit (Figure 9 and Figure 10) to convert the single-ended signal provided by the PSOC to a differential signal displayed unexpected nonlinearity (Figure 11). It is hypothesized that the nonlinearity was caused by RF interference from the PCB design. In the next version of the printed circuit board, a capacitor circuit will be included to reduce RF interference.

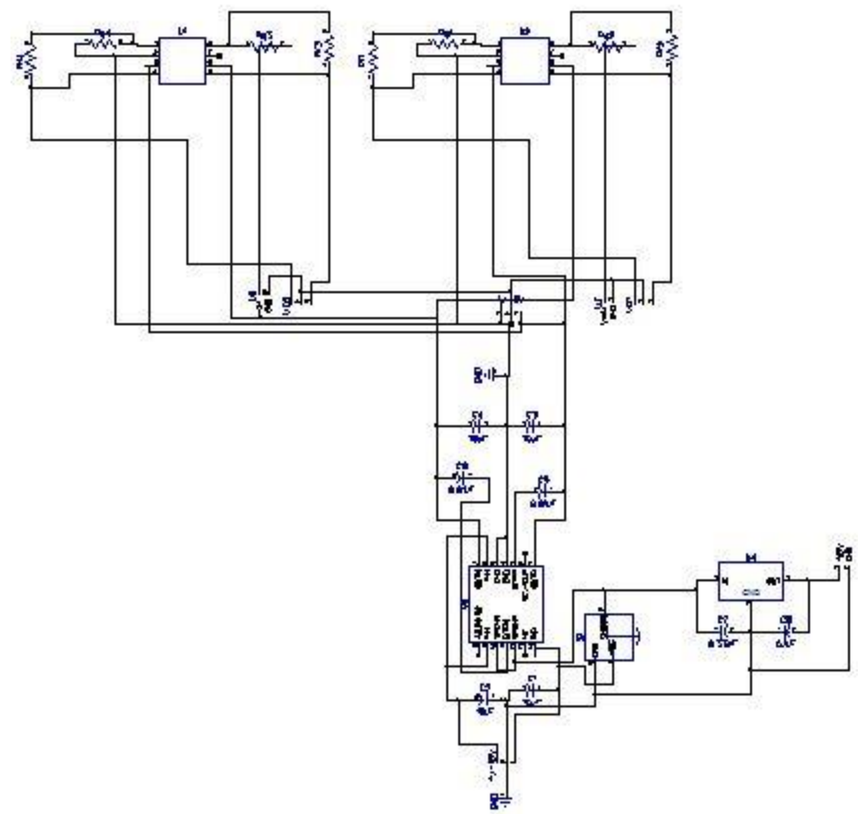


Figure 9 Board schematic

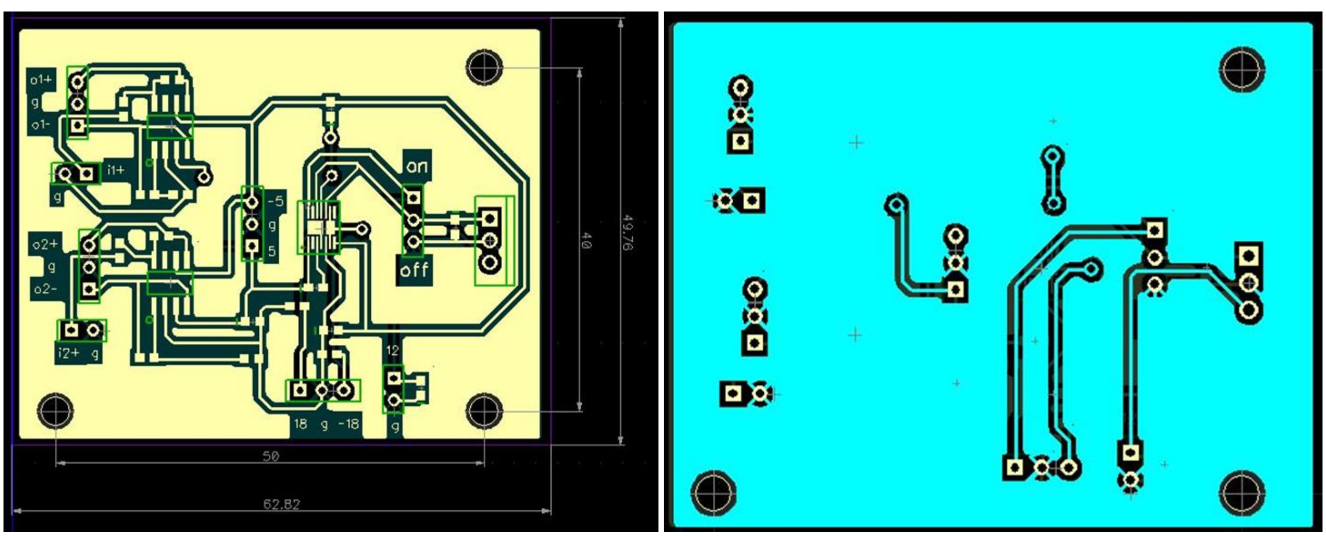
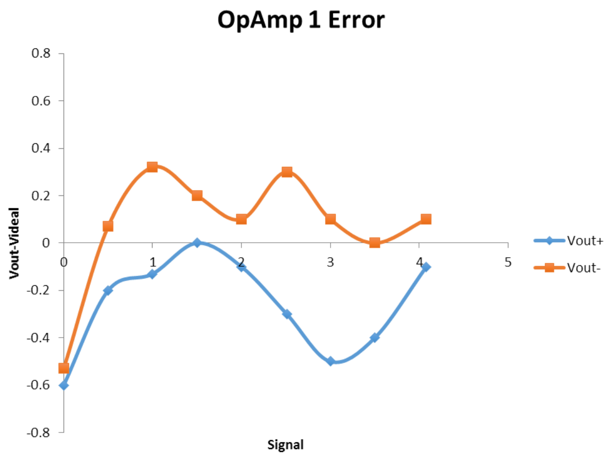


Figure 10 Schematics of board layouts top (left) and bottom (right)



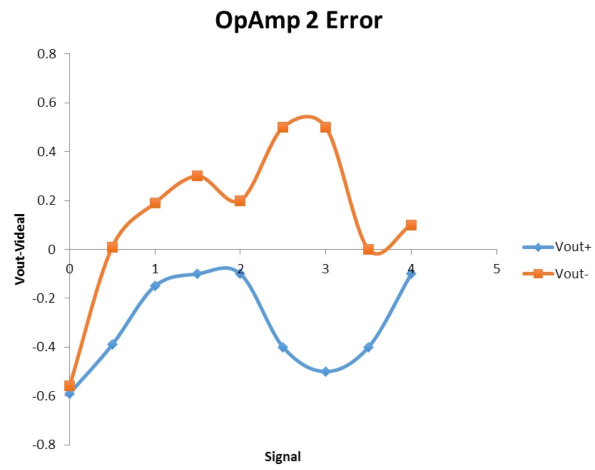


Figure 11 Figures show the characterization of the nonlinear response of current op amps.

Software

The USB->UART connection between the PSoC and the PC required significant debugging and signal probing to understand its protocol so that we could design our code to work with it. The PSoC USBUART communication was easy to setup and get working with example code supplied by Cypress; however the actual data rate while streaming packets containing single coordinates (3 bytes) across the USBUART connection was not as fast as we expected and needed it to be. We found that even though the USBUART connection can be set to any arbitrary baud rate, empirical speed tests indicated that the baud rate did not affect the actual data rate. By setting up digital output pins to trigger when packets of data were received, we found that the PSoC UART buffer receives a whole packet every 250us, regardless of baud rate and packet size. We verified this packet reception interval with an Arduino as well. With his knowledge, we increased the data packet size to 5 coordinates (15 bytes), which then brought the data streaming rate up to desired 20k coordinates per second.

Additionally, getting the timer interrupts setup for the PSoC took a bit of debugging. The Interrupt blocks are quite flexible; enabling the user to select how and if the interrupt routine exits using a register. In our initial code, we didn't know that we had to reset the register in order for the interrupt to be reset, and it took us a while pouring over the datasheets and application notes to find the exact function that we needed to call.

Future Improvements

Most recommended changes to the design concern the hardware selection. We believe that the choice of software and implementation scheme were appropriate for the stated goals of the project. Recommended changes are presented below.

Galvanometers- Increase the Speed

The current galvanometers used in the project were selected primarily because of their low cost. However, upon implementation, it was discovered that their speed of 20Kpps (points per second) was insufficient to project most ILDA images (<1000 points) at the desired rate of 30 Hz (necessary for proper viewing by the human eye). Better galvanometers capable of more points per second would improve the image quality and allow projection of more complicated images (more points per image).

Op-Amp Nonlinearity

As mentioned previously, unexpected nonlinearity in the differential op amps restricted the angle to which the galvanometers could be driven, and thus the size of the projected image. The op amps were intended to provide the galvanometers with a differential +/-5V signal, allowing the mirrors to span a 20 degree range in both axes. Instead, the single-ended +4 volt signal supplied by the PSoC was sufficient for 8 degree swings in each axis. While not a problem for projection at a distance, this makes the demonstration of the laser at close range ineffective - except for personal-sized projections at intimate venues. Resolving the nonlinearity would allow for a broader range of image sizes.

Bluetooth Connectivity

It is possible to write code to allow the connection between the PC and laser projector via Bluetooth. This would allow the projector to be installed and used in less accessible places, increasing its versatility as a communication tool.

Multi-contour images Bug

During multi-contour detection mode, the laser projector exhibits a bug causing the laser to be energized between contours. This leads to laser traces between main shapes, often making multi-contour images difficult to see clearly. Fixing this error should not be a difficult task because of the nature of the data stream that is fed to the PSoC. The three-dimensional data stream contains x and y coordinates in addition to the on/off state of the laser between coordinates. To properly resolve the multi-contour image, the laser should be off while traveling from the last point of one contour to the first point of another.

Bill of Materials

Component	Supplier	Cost (USD)
Laser & driver		$30
MicroProcessor	Cypress PSoC 5LP CY8CKIT	$100
Galvanometers & drivers		$120
Power Supply		included with galvos
Printed Circuitboard	Boardmilled in-house	$4
OpAmps & passives	Texas Instruments THS4150	$12
LDO Voltage Regulator & passives		$8
Enclosure	Lasercut Plywood ¼”	$10
Fasteners	McMasterCarr	$10
Laser Mounting Bracket & Laserguard	Fuse Deposition Modeled using ABS plastic	$6
Misc wire/solder/headers		$4
Total		**$304**