

Self-Calibrating Long-Exposure Laser Light Painter

ECE 445 Design Document, Fall 2026

Team: #30

Alex Chen (alex18), Billy Huang (billyh2), Michael Shi (mwshi2)

Professor: Prof. Viktor Gruev

TA: Denghan Xiong

1 Introduction

1.1 Problem and Solution

Long-exposure light painting is done by hand, so a drawing is hard to repeat or reproduce exactly. A laser steered by galvanometer mirrors can draw a vector image while a camera shutter stays open, but the hobby galvo kits these projects are built around never measure their own output. Two errors show up in the photograph. The mirror geometry and galvo scale error distort the image, and the beam slows at corners and speeds up along straight segments, so exposure varies along a stroke. The camera integrates every error over the exposure, producing bent lines, bright blobs where the beam lingered, and strokes that fade where it moved too fast.

Hobby laser projectors are often built by people with no laser safety training, and a beam that goes somewhere other than where it was commanded is the failure behind laser strikes on aircraft. Pilots reported 10,994 laser strikes to the FAA in 2025, a 14 percent drop from the year before [1]. A projector that measures where its beam lands, and whose optical power is capped by parts that firmware cannot change, is easier to trust than an open-loop command path that no sensor checks.

We are building a laser light-painting instrument around a custom controller PCB. A pair of closed-loop galvos steer a 659 nm laser onto a white target board 1 m away in a darkened room, while a DSLR beside the optical head holds its shutter open. The controller measures where the beam lands with a removable photodiode calibration target mounted on the face of the board, fits a two-dimensional geometric

correction to those measurements, and adjusts laser power with beam velocity so each stroke receives even exposure along its length. The two-axis demonstration runs on the galvo kit's own amplifier. Alongside it we design and characterize one custom galvo servo daughtercard (loop compensation, current sensing, and a bipolar power stage) that closes the loop on one axis using the position signal the kit driver already produces. Lifting the kit driver's output link for that axis acts as a hardware selector, so the kit and the daughtercard can never drive the same coil.

Reach goals, in order: a small learned residual model trained on recorded trajectories to correct what the static calibration misses, trained on a laptop with inference bounded enough to run on the microcontroller; a second custom servo channel; and drawing to music.

1.2 Visual Aid

The laptop converts an SVG into a stroke file and sends it to the controller over USB. The controller drives the galvos and laser on the optical plate, which project onto the target board 1 m away, and it opens and closes the DSLR shutter through isolated relay contacts. The calibration target is mounted on the board only during calibration.

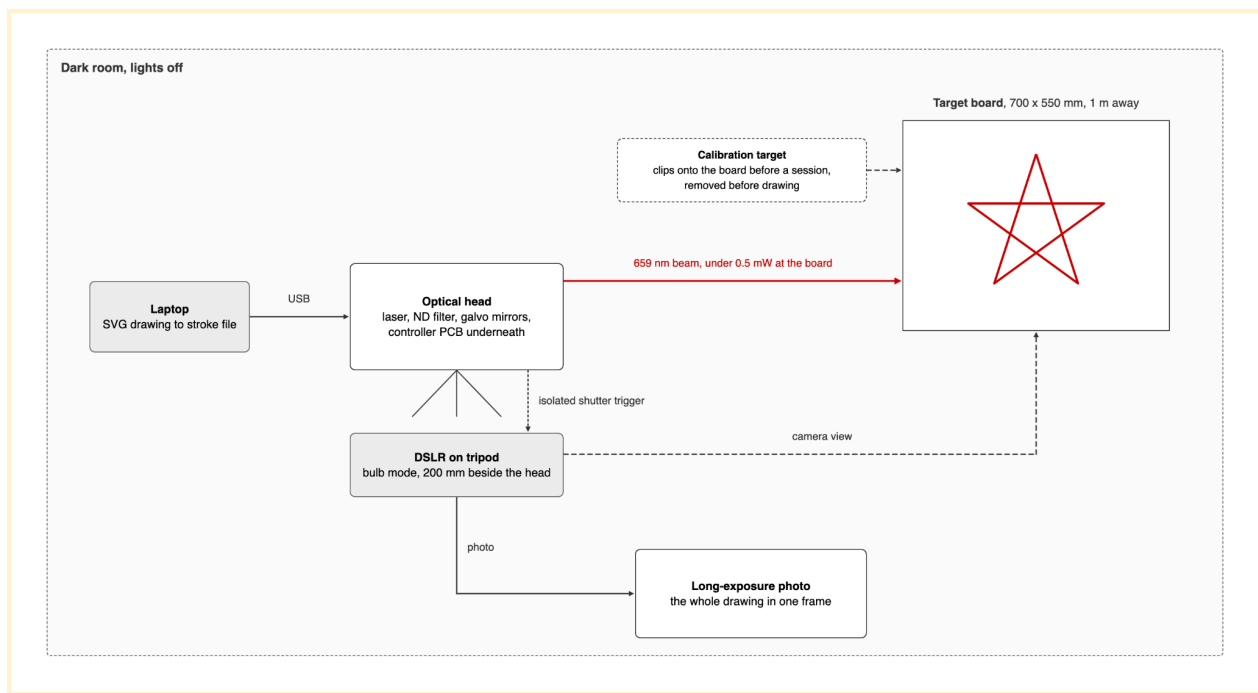


Figure 1: Visual aid of the light painter in use

1.3 High-Level Requirements

To consider the project successful, the system must meet all of the following:

- After geometric calibration, the system reproduces a commanded image on the target board with a position error of at most 3 mm RMS and 6 mm maximum, measured against a printed checkerboard over at least 25 held-out test points not used to fit the calibration, across a field at least 500 mm wide at a 1 m projection distance.
- With velocity compensation enabled, stroke brightness in an unclipped RAW photograph stays within 20% of a single reference exposure level taken across the whole drawing, measured on a test pattern containing a straight segment, a curve, and a 90 degree corner drawn at the nominal 100 mm/s stroke speed, excluding a 5 mm region around corners and blanking points.
- Geometric calibration reduces RMS position error by at least 60% compared with the uncorrected system, measured on the same held-out test points, so the improvement comes from the correction and not from the raw galvo accuracy.

The proposal's third requirement was a latched hardware interlock. We replaced it because the accessible power is already held in Class 2 by two passive limits (Section 2.3.3) that cannot fail toward higher power, and because the interlock added a regulator, window comparators, a one-shot, and a stall detector without changing the hazard class. The new third requirement measures what this project is about: whether the calibration works.

2 Design

2.1 Block Diagram

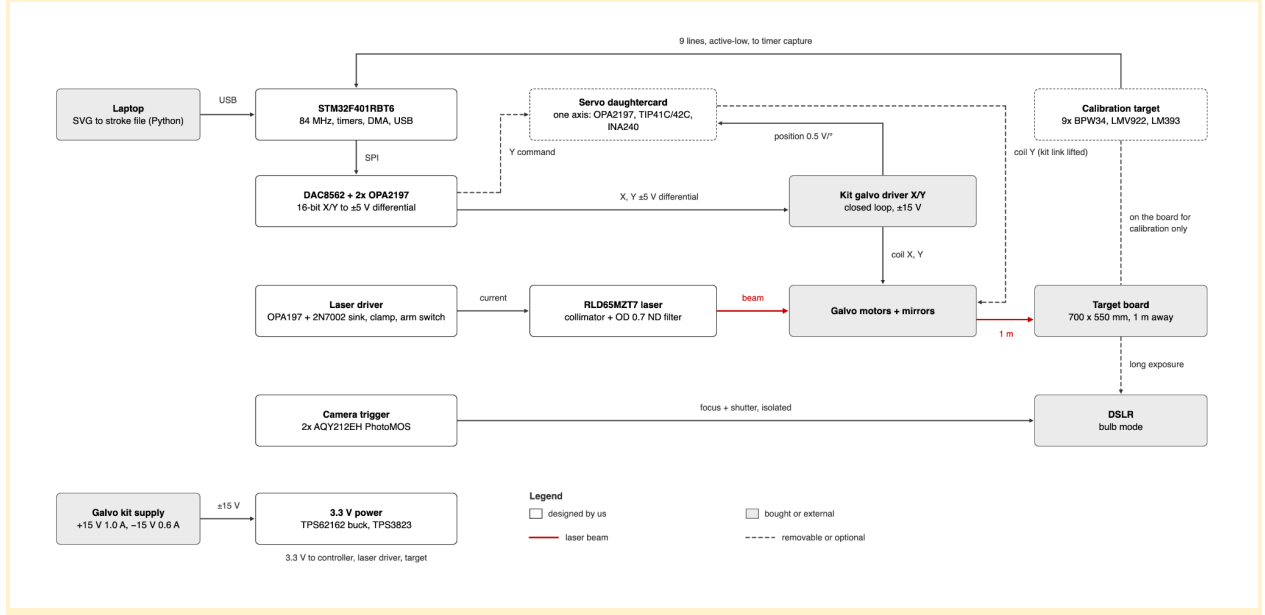


Figure 2: System block diagram

The design has six subsystems that can be built and tested separately. The controller reads stroke files, applies the calibration, and streams the X/Y commands, the laser power command, the laser enable, and the shutter signals. The photodiode calibration target is the only measurement of where the beam lands and feeds the calibration fit. The laser driver sets optical power from the commanded beam velocity and clamps the maximum power in hardware. The servo daughtercard replaces the kit amplifier on one axis for characterization. The camera trigger and power subsystem supplies the rails and triggers the shutter through isolated contacts. The optomechanics hold the fixed 1 m projection geometry shown in Figure 3.

2.2 Physical Design

Figure 3 shows the physical arrangement. The 659 nm laser and collimator, the bonded ND filter, and the X/Y galvos sit on a 300 mm optical plate on the optical-head tripod with the controller PCB below. The beam runs 1000 mm to a 700 x 550 mm diffuse white target board, which leaves a 100 mm margin around the 500 mm field. The camera is on its own tripod outside the optical plane. Table 1 summarizes the dimensions.

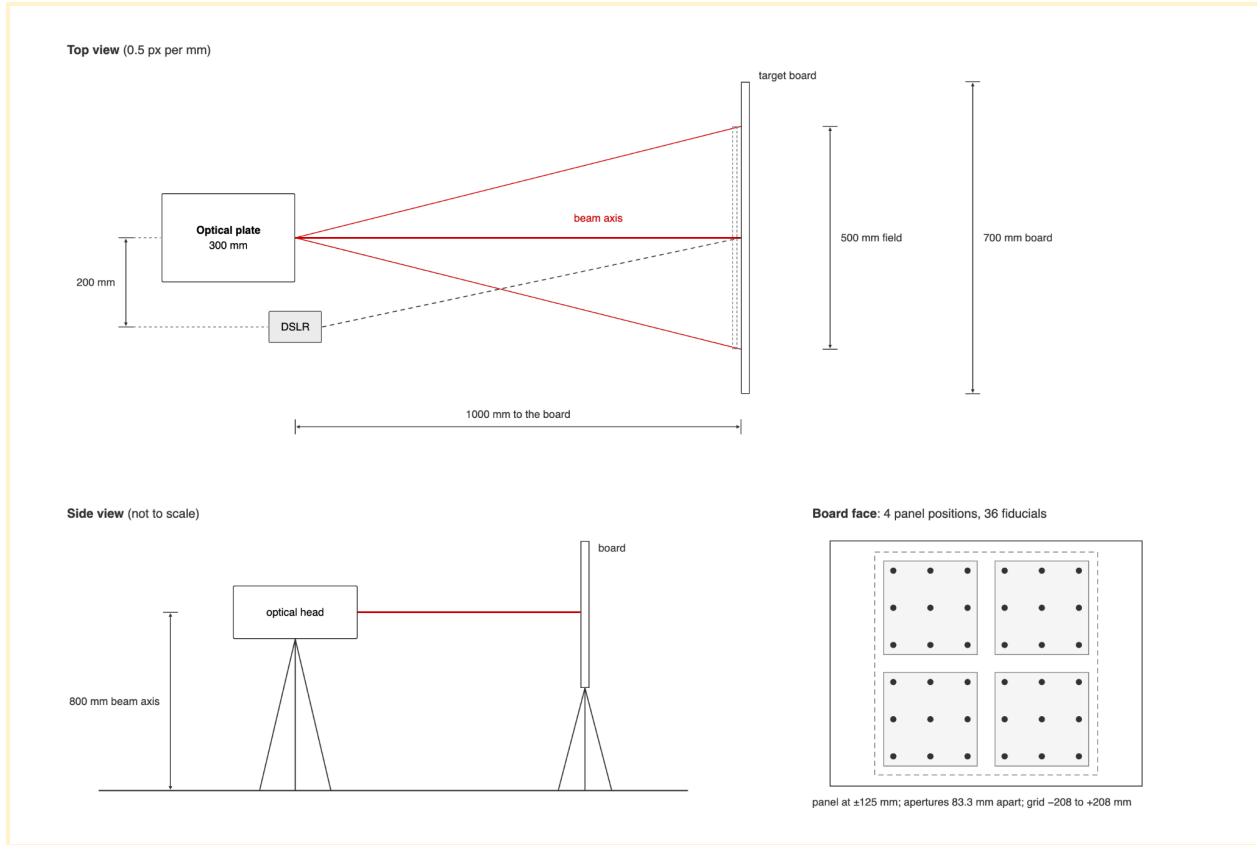


Figure 3: Open-bench layout of the optical head, target board, camera, and calibration positions

Table 1: Physical dimensions

Item	Dimension	Reason
Galvo pivot to target board	1000 mm	Beam path shown in Figure 3
Target board (diffuse white)	700 x 550 mm	100 mm margin; beam terminates on the board
Optical plate	300 mm long	Mounts the laser, collimator, ND filter, galvos, and controller PCB
Beam-axis height	800 mm above floor	Below standing eye height; aligns the two tripods
Camera offset	200 mm out of the optical plane	Keeps the camera clear of the beam path
Calibration panel positions	4, at ± 125 mm in x and y	Spreads 36 fiducials across the

		field
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The optical head and board share an 800 mm beam-axis height, and the camera sits 200 mm outside the optical plane. The calibration panel mounts at four positions on the board face, so its nine detectors measure 36 points spread across the whole field. In a darkened room, the bonded ND filter and the hardware current clamp keep board power below 0.50 mW (Class 2).

2.3 Subsystems

2.3.1 Controller and Embedded Processing

The controller applies the geometric correction, so HLR 1 and HLR 3 depend on it, and it sets the velocity-dependent laser command for HLR 2.

An STM32F401RBT6 (Cortex-M4F with FPU, 84 MHz, 128 KB flash, 64 KB RAM, supplied by the ECE E-Shop) [3] reads a stroke file over USB from the laptop, applies the stored correction to each vertex, and streams the corrected X/Y pair to a DAC8562SDGSR dual 16-bit DAC [4] over SPI. USB full-speed needs an accurate 48 MHz clock, which the internal oscillator cannot provide, so the board carries an 8 MHz crystal for the PLL. A hardware timer triggers each DMA transfer, so the update rate is fixed by the timer and not by firmware timing. One OPA2197ID dual op amp per axis [5] converts each DAC output into the ILDA differential command, ± 5 V per axis into the kit's 200 k Ω inputs [2]. The firmware also sets the laser power command, asserts the laser enable line, and drives the two camera relays. Nine active-low lines from the calibration target go to timer capture inputs. Firmware is developed on a NUCLEO-F401RE before the controller PCB arrives.

At the 50 kHz update rate, a 100 mm/s stroke is sampled every

$$\Delta s = v / f_s = (100 \text{ mm/s}) / (50 \text{ kHz}) = 2 \text{ } \mu\text{m} \quad (1)$$

and a 200 ns timing jitter moves a sample by $100 \text{ mm/s} \times 200 \text{ ns} = 0.02 \text{ } \mu\text{m}$, which is negligible. The galvos are rated for 20 kpps on the ILDA test pattern [2], so 50 kHz oversamples the command and the galvo filters it to a smooth path. Each update needs two 24-bit SPI frames. With SPI1 at $84 \text{ MHz} / 4 = 21 \text{ MHz}$ that is $2.3 \text{ } \mu\text{s}$ of the $20 \text{ } \mu\text{s}$ update period (11.5%). The degree-3 correction has 10 terms per axis, about 40 floating-point operations per vertex, which takes under $2 \text{ } \mu\text{s}$ on the FPU against the $20 \text{ } \mu\text{s}$ requirement. The timer capture clock is 84 MHz, a resolution of 11.9 ns.

Interfaces: USB full-speed CDC from the laptop; ± 5 V differential X/Y into 200 k Ω (25 μ A per line); 0 to 3.3 V laser power command, 3.3 V enable, and 3.3 V blank to the laser driver; nine active-low capture inputs from the target (pulled up on the target board, no MCU pull-ups); two GPIO to the camera relays.

Controller PCB (rev A, PCB round 3): block-level schematic with the proposed pin map
Grey = connector to another board or bought module. Dashed = optional.

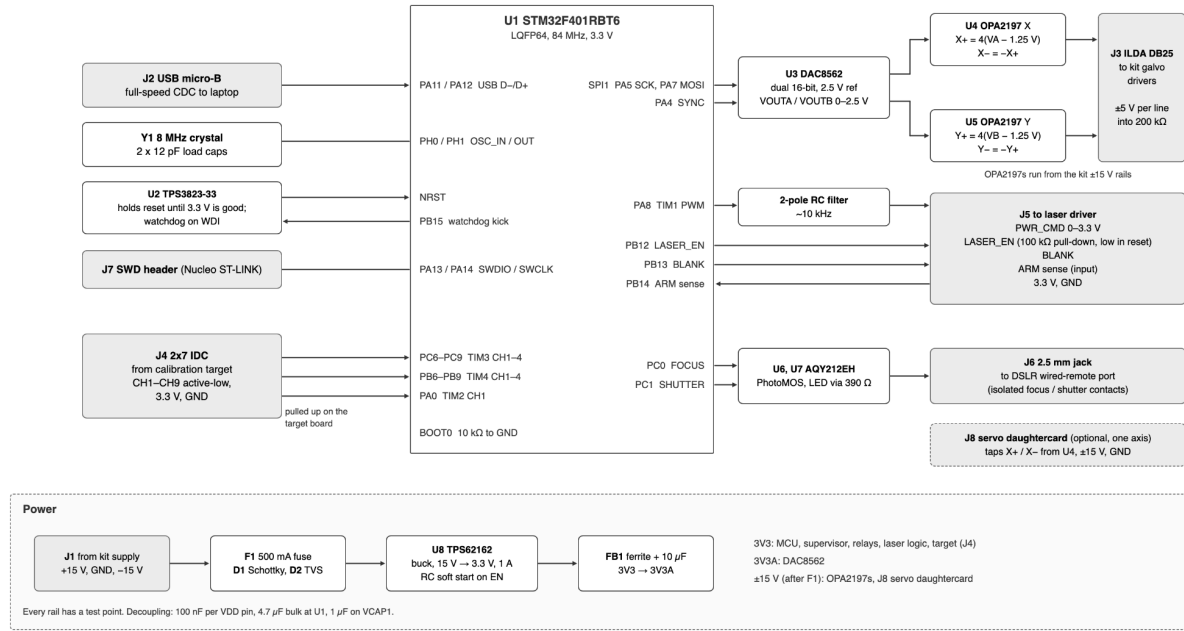


Figure 4: Controller block-level schematic and proposed pin map

Table 2: Controller Requirements and Verification

Requirements	Verification
Update the X/Y command pair at a fixed 50 kHz with jitter under 200 ns.	Toggle a spare GPIO from the DMA-complete event; capture 10 s on an oscilloscope; confirm a 20.00 μs mean period and under 200 ns peak-to-peak variation.
Evaluate the stored polynomial correction for one vertex in under 20 μ s.	Read the DWT cycle counter around the correction routine for 10,000 random vertices; confirm the worst case is under 1680 cycles (20 μs at 84 MHz).
Capture comparator edges with a timer resolution of 20 ns or better.	Feed a 10.000 μs pulse from a function generator into a capture input; confirm 840 ± 1 counts at 84 MHz (11.9 ns per count).

Hold the laser enable line low at reset and during firmware update.	Probe the enable line while holding the MCU in reset and during a full firmware flash; confirm it never rises above 0.4 V.
Produce a full-scale X/Y command of $\pm 5.00 \text{ V} \pm 0.05 \text{ V}$ per axis.	Write codes 0 and 65535 to each channel; measure the differential output at the galvo connector with a 6.5-digit DMM and confirm all four readings.

2.3.2 Photodiode Calibration Target

The target is the only measurement of where the beam lands, so HLR 1 and HLR 3 depend on it. It hands the controller nine digital lines and nothing else, and it is removed before drawing.

Nine BPW34 photodiodes [6] sit behind 1 mm apertures in a 210 mm square of 3 mm black cast acrylic, on an 83.3 mm grid. The apertures are laser cut, which holds their centers to about $\pm 0.1 \text{ mm}$. A square of red transparent acrylic in front of each photodiode passes the laser and blocks most stray light; each photodiode and filter sit in a black 3D-printed holder glued behind its aperture. The panel mounts on registration pins (one round hole and one slot) at four offsets of $\pm 125 \text{ mm}$. Because 125 mm is 1.5 times the pitch, the four placements interleave into one 6 x 6 grid of 36 fiducials, 83.3 mm apart, from -208 mm to $+208 \text{ mm}$.

The sensor PCB is 80 x 80 mm and was ordered in PCBWay round 1. Each channel is one half of an LMV922 dual op amp [7] wired as a transimpedance amplifier (TIA), followed by one half of an LM393 dual comparator [8]. Five of each package serve nine channels; the spare halves are tied off. The TIA's non-inverting input sits at $V_{REF} = 3.3 \text{ V} \times 1 \text{ k}\Omega / 34 \text{ k}\Omega = 0.097 \text{ V}$, so the output never has to swing to ground. The comparator threshold V_{TH} is set to 0.15 V with a 1 k Ω trimmer, and 10 k Ω / 1 M Ω positive feedback adds 31 mV of hysteresis, which keeps the slow edges from chattering. The LM393 output is open collector with a 5.1 k Ω pull-up to 3.3 V and a channel LED, so each line is high in the dark and pulls low while the spot is on its aperture.

When the beam sweeps across an aperture, the controller timestamps both comparator edges and takes the midpoint as the beam center. Because the turn-on and turn-off thresholds differ, the midpoint shifts slightly in the sweep direction; the firmware repeats the sweep in the opposite direction and averages, which cancels this shift together with the comparator delay.

At the 100 mm/s sweep speed, the beam takes $(1 \text{ mm})/(100 \text{ mm/s}) = 10 \text{ ms}$ to cross the aperture. The simulated pulses below last 14 to 26 ms, above the 5 ms requirement. The fraction of a Gaussian beam ($1/e^2$ radius $w = 0.75 \text{ mm}$) passing a centered aperture of radius $a = 0.5 \text{ mm}$ is:

$$T = 1 - \exp(-2a^2/w^2) = 1 - \exp(-2(0.5)^2/(0.75)^2) = 0.59 \quad (2)$$

Calibration sweeps run at a reduced board power of 0.30 mW. With 90% filter transmission and about 0.40 A/W BPW34 responsivity at 659 nm [6], the peak photocurrent is

$$I_{pd} = 0.30 \text{ mW} \times 0.59 \times 0.90 \times 0.40 \text{ A/W} = 64 \text{ } \mu\text{A} \quad (3)$$

and the TIA peak is

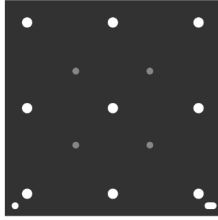
$$V_{pk} = V_{REF} + I_{pd} \times R_f = 0.097 \text{ V} + 64 \text{ } \mu\text{A} \times 10 \text{ k}\Omega = 0.73 \text{ V} \quad (4)$$

The gain is held at 10 k Ω because the LM393 inputs only work up to $V_{CC} - 2.0 \text{ V}$ over temperature, 1.3 V on a 3.3 V supply [8]. At the full 0.50 mW drawing power the same calculation gives 106 μA and 1.16 V, which still fits but leaves no margin, so calibration uses the lower power. A 10 nF feedback capacitor sets the bandwidth to $1/(2\pi \times 10 \text{ k}\Omega \times 10 \text{ nF}) = 1.6 \text{ kHz}$, a 100 μs time constant against a pulse that lasts tens of milliseconds.

We simulated the board in ngspice [9], with the netlist generated from the KiCad schematic and manufacturer models for both ICs. The dark TIA output is 0.096 V and the outputs sit at 3.28 V. The output drops when the TIA rises past 0.181 V and releases when it falls back below 0.150 V, matching the designed 31 mV hysteresis. A 2 mm spot crossing an aperture at 100 mm/s, with 300 nA rms of added input noise, produced exactly one falling and one rising edge at every tested signal level: 14 μA (0.24 V peak, 13.9 ms pulse), 40 μA (0.50 V, 21.8 ms), and 80 μA (0.90 V, 25.7 ms). Lighting one channel moved V_{TH} by 1.3 mV and left the other eight outputs high. The TIA step response is first order with no overshoot.

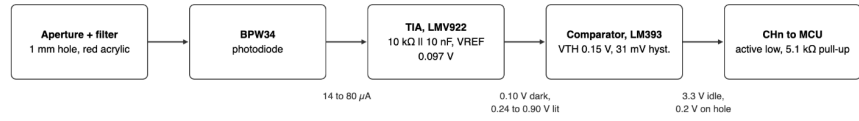
Interfaces: J2 (2x7 IDC ribbon to the controller) carries 3.3 V, ground, and nine active-low open-collector outputs, high above 2.9 V and low below 0.4 V; supply current is about 8 mA dark and under 25 mA with every channel lit. J1 (2x10 IDC ribbon, about 300 mm) brings in the nine photodiodes, each signal wire next to its own ground.

(a) Photodiode panel, 210 mm square



9 apertures, 1 mm, 83.3 mm pitch (white); M3 holes for the PCB (grey); round hole + slot for the pins

(b) One channel (x9)



(c) ngspice simulation: 40 μ A spot crossing at 100 mm/s, from the KiCad netlist

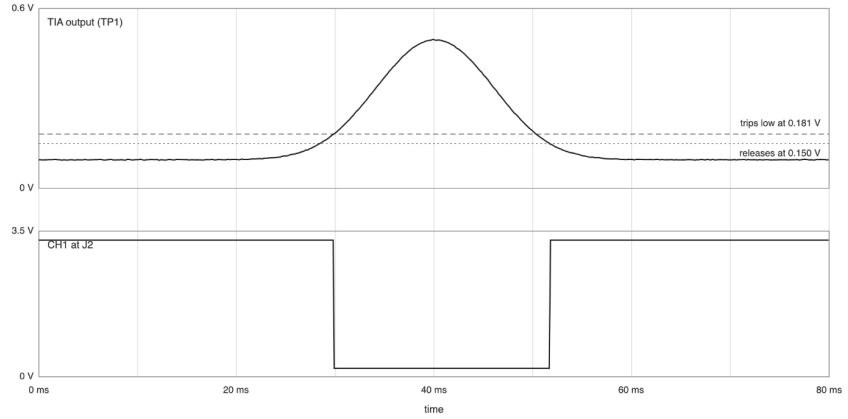


Figure 5: Calibration target geometry, one channel's circuit, and the simulated crossing

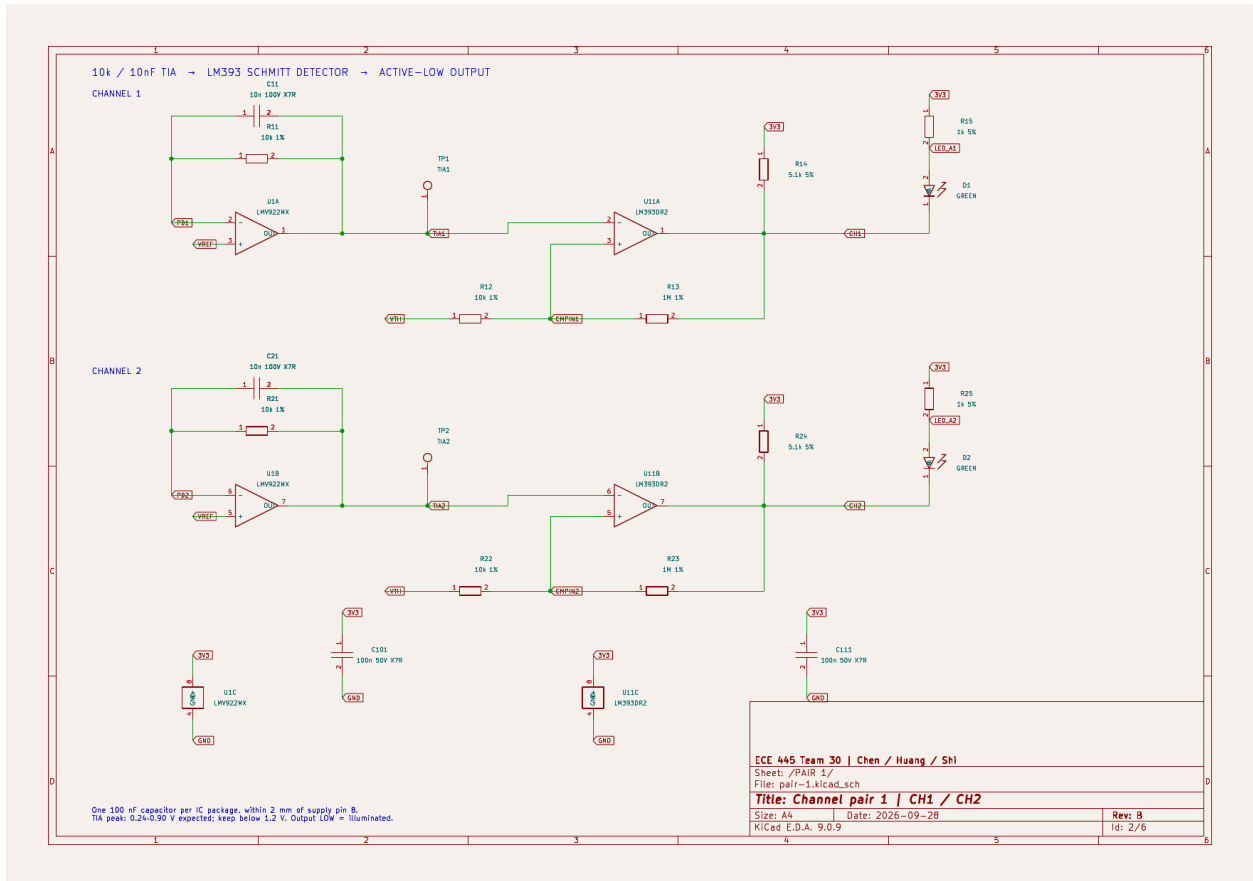


Figure 6: Calibration target schematic, channel pair 1 (KiCad). The other four sheets repeat it; U5B and

U15B are tied off.

Table 3: Calibration Target Requirements and Verification

Requirements	Verification
Produce a comparator pulse of at least 5 ms when the beam crosses an aperture at 100 mm/s.	• Sweep the beam across each aperture at 100 mm/s; measure each output pulse width on the oscilloscope; confirm all nine are at least 5 ms.
Keep the TIA peak between 0.24 V and 1.2 V at calibration power, so it is above threshold and inside the LM393 input range.	• Park the beam on each aperture at calibration power; read TP1 to TP9 with a DMM; confirm every reading is between 0.24 and 1.2 V.
Maintain at least 40 dB signal-to-noise ratio at the comparator input in the darkened room.	• With the laser off, measure RMS TIA output on each channel; park the beam on each aperture; confirm $20 \log_{10}(\text{peak above dark level} / \text{RMS noise})$ is at least 40 dB.
Produce exactly one falling and one rising edge per crossing.	• Sweep each aperture 20 times in each direction; count edges on the oscilloscope; confirm two edges per crossing with no chatter.
Hold aperture center positions to ± 0.1 mm, and repeat registration between the four offsets to ± 0.1 mm.	Measure each aperture center against the registration pins; mount and remove the panel 10 times at one offset; confirm position and repeat registration are each within ± 0.1 mm.
Deliver all nine channels as 3.3 V active-low logic into the controller capture inputs.	Probe each output at the controller connector during a crossing; confirm high above 2.9 V and low below 0.4 V on all nine.

2.3.3 Laser Driver and Exposure Control

This subsystem delivers HLR 2 and holds the optical-power ceiling that keeps the open-bench instrument in Class 2.

Driver. A constant-current sink built from an OPA197IDR error amplifier [11], a 2N7002 MOSFET, and a $10\ \Omega$ sense resistor drives an RLD65MZT7 diode (659 nm typical, 7 mW maximum) [10]. The diode's monitor photodiode closes an outer power loop, so optical output tracks the command rather than the current alone. The reference into the current sink is the lower of the power loop's output and a fixed divider voltage, so the divider hard-clamps the maximum current regardless of the command or firmware. A fixed OD 0.7 neutral density filter after the collimator sets the accessible emission. The diode runs from the 3.3 V rail: at the clamp current the sense resistor drops about 0.24 V and the diode at most 2.6 V [10], which leaves about 0.4 V for the sink MOSFET and the arm MOSFET.

Operating point. From the datasheet, the threshold current I_{th} is 20 mA typical and the operating current is 28 mA at 5 mW, a slope efficiency of $\eta \approx 0.63\ \text{mW/mA}$ [10]. The power at the board is

$$P_{\text{board}} = TND \cdot \eta \cdot (I - I_{th}), \quad TND = 10^{-0.7} = 0.20 \quad (5)$$

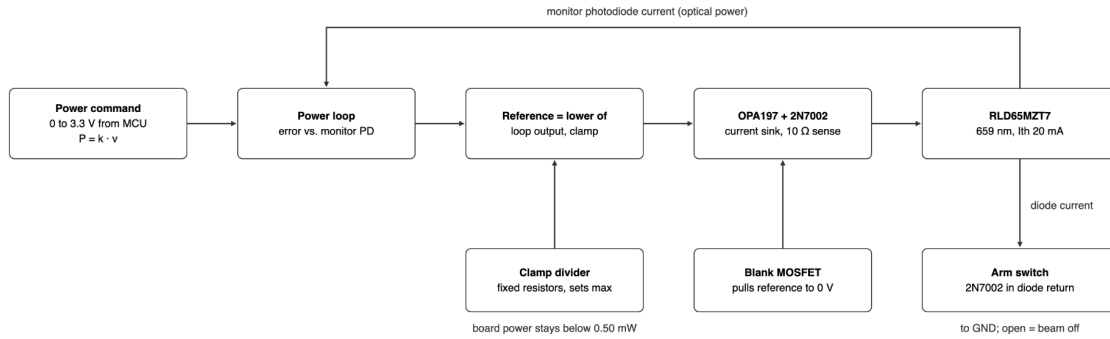
so 0.50 mW at the board needs 2.5 mW from the diode, about 24 mA for a typical part. The clamp divider is set from each diode's measured L-I curve so board power stays below 0.50 mW. Normal drawing uses an optical power command proportional to beam velocity, limited by that clamp.

Exposure control. Exposure per unit length is proportional to P/v . The firmware therefore commands $P = k \cdot v$, blanks below a minimum velocity and during retrace, and fits k from RAW photographs of test strokes drawn at five fixed speeds. The power loop targets about 3 kHz bandwidth to settle within 200 μs . Blanking grounds the current-sink reference through a MOSFET, so current falls in a few microseconds, well inside the 100 μs requirement.

Arm switch. A panel toggle switch drives a second 2N7002 in series with the diode return path. With the switch open, no current can flow through the diode no matter what the controller commands, so the beam stays off until an operator arms it. The switch also reports its state to the firmware.

Interfaces: 0 to 3.3 V power command, 3.3 V enable, and 3.3 V blank from the controller; arm switch state to a controller GPIO; 3.3 V supply.

(a) Laser driver



(b) Blanking response (requirement)

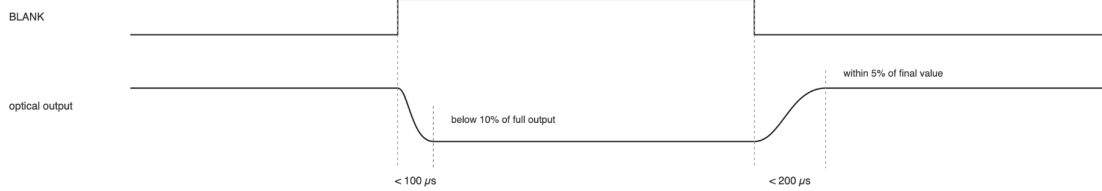


Figure 7: Laser driver and blanking response

Table 4: Laser Driver Requirements and Verification

Requirements	Verification
The installed ND filter and hardware current clamp keep board power below 0.50 mW regardless of command.	Wear OD 2+ glasses at 659 nm; measure diode output with the filter removed and board-plane power with the filter installed, both at maximum command; confirm the clamp keeps board power below 0.50 mW.
Laser current tracks the command within ± 0.5 mA from threshold to the clamp current.	Step the command in 1 mA increments from threshold to the measured clamp current; measure the sense-resistor voltage; confirm each reading is within ± 0.5 mA of command.
Blank optical output within 100 μ s of the blanking command and reach steady output within 200 μ s of unblanking.	Place a fast photodiode in the beam and scope it with the blank line; confirm optical output falls below 10% within 100 μs on 20 trials and settles within 5% of final value within 200 μs after unblanking.

Opening the arm switch drops diode current below threshold within 10 ms, with the controller commanding full power.	• Command maximum power; open the arm switch; scope the sense-resistor voltage; confirm current is below 20 mA within 10 ms on 10 of 10 trials.
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2.3.4 Custom Galvo Servo Daughtercard

The daughtercard is the main custom analog design. It is not on the critical path for the high-level requirements: the final two-axis image uses the kit amplifiers, and the daughtercard is demonstrated and characterized on one axis.

An OPA2197ID forms the error signal (command minus position) from the controller command and the kit driver's buffered position output (0.5 V/degree). A second OPA2197ID stage is a lead-lag compensator with a notch at the first mirror resonance. The output stage is a complementary TIP41C/TIP42C class-AB pair [12] on the kit's ± 15 V rails, driving the coil through a $0.05\ \Omega$ shunt read by an INA240A2D [13] (gain 50 V/V, so 2.5 V/A around a 2.5 V reference, powered from a local 5 V regulator). A clamp on the compensator output limits coil current to ± 1.0 A. The kit driver's output link is lifted on that axis, so only one amplifier can drive the coil at a time.

A moving-magnet galvo is close to a double integrator, $K/(Js^2)$, up to its first resonance. Settling a 10-degree step to 2% in 5 ms with damping ratio $\zeta = 0.7$ requires

$$t_s \approx 4/(\zeta\omega_n) \leq 5\text{ ms} \Rightarrow \omega_n \geq 1143\text{ rad/s (182 Hz)} \quad (6)$$

We target a 1 kHz crossover with at least 45 degrees of phase margin, about five times the required bandwidth. The lead zero and pole sit about three times below and above crossover. Final component values are set after a swept-sine measurement of the kit-driven galvo, which gives the resonance frequency, coil resistance and inductance, and full-swing current.

If the coil resistance is $3\ \Omega$ (a placeholder until measured), the worst-case continuous dissipation per transistor at the 1 A clamp is

$$P = (15\text{ V} - 1\text{ A} \times 3\ \Omega) \times 1\text{ A} = 12\text{ W} \quad (7)$$

With a $150\ ^\circ\text{C}$ maximum junction temperature, $25\ ^\circ\text{C}$ ambient, $\theta_{JC} = 1.92\ ^\circ\text{C/W}$, and a $0.5\ ^\circ\text{C/W}$ pad, each TO-220 needs a heatsink of $8\ ^\circ\text{C/W}$ or better.

If the loop does not meet the step and hold requirements by the progress demo (week of November 2), the final demonstration uses the kit amplifier and the daughtercard is presented as a characterized subsystem with measured Bode plots.

Interfaces: ± 5 V command from the controller; 0.5 V/degree position from the kit driver; ± 15 V from the kit supply (up to 1.0 A); coil connection through a breakout cable.

Table 5: Servo Daughtercard Requirements and Verification

Requirements	Verification
The servo holds a static point within 1 mrad optical (1 mm at 1 m) for 10 minutes after a 15-minute warm-up.	• Run the servo for 15 minutes on a test pattern. • Park the beam on a mid-field point over a ruled target on the board. • Photograph the spot at $t = 0$ and every minute for 10 minutes. • Confirm the spot center never moves more than 1 mm from its starting position.
The servo settles a 10-degree optical step to within 2% in 5 ms.	• Command a 10-degree step. • Capture the kit position output on the oscilloscope. • Measure the time until the signal stays within ± 0.2 degrees of its final value; confirm it is at most 5 ms.
The loop has at least 45 degrees of phase margin at crossover.	• Inject a swept sine at the summing node. • Measure loop gain with the lab network analyzer, or with the oscilloscope and a Bode script. • Read the phase at the 0 dB crossing and confirm it is at least 45 degrees from -180.
Coil current never exceeds $1.0 \text{ A} \pm 0.1 \text{ A}$, including on a full-scale step.	• Command a full-scale square wave. • Capture the INA240 output on the oscilloscope and convert at 2.5 V/A. • Confirm the peak is at most 1.1 A.
Heatsinks stay below 70°C during a 10-minute ILDA test pattern.	• Attach a thermocouple to each heatsink. • Run the ILDA test pattern for 10 minutes and log temperature; confirm the maximum is below 70°C.

2.3.5 Camera Trigger and Power

This subsystem supplies clean rails and triggers the camera without an electrical connection.

Power. The galvo kit's supply (+15 V at 1.0 A, -15 V at 0.6 A) [2] feeds the whole system. A TPS62162DSGR buck regulator (3 to 17 V in, 1 A out) [14] makes 3.3 V, followed by a ferrite bead and $10 \mu\text{F}$ LC filter for the analog section. Its 2 x 2 mm leadless package is soldered with hot air or the lab

oven. A TPS3823 supervisor [15] holds the MCU in reset until the rail is good. The +15 V input to the controller has a 500 mA fuse, a series Schottky diode for reverse polarity, a TVS diode, and an RC soft start on the regulator enable. Every rail has a test point. Table 6 gives the 3.3 V load budget.

Table 6: 3.3 V load budget

Load	Current (mA, typical)
STM32F401 at 84 MHz, all peripherals on [3]	32
Calibration target (9 channels, every LED lit)	25
Laser diode at clamp	26
Two AQY212EH input LEDs	11
DAC8562, supervisor, indicator LEDs	20
Total	114

114 mA is 11% of the regulator's 1 A rating. At about 88% efficiency the regulator draws

$$I_{15V} = (3.3 \text{ V} \times 0.114 \text{ A}) / (0.88 \times 15 \text{ V}) = 29 \text{ mA} \quad (8)$$

from the +15 V rail. The kit drivers' own +15 V draw at full swing will be measured during kit bring-up to confirm the 1.0 A supply is sufficient.

Camera trigger. Two AQY212EH PhotoMOS relays [16] act as the focus and shutter contacts of a wired remote. Each input LED is driven from a GPIO through 390 Ω , giving $(3.3 - 1.25)/390 = 5.3 \text{ mA}$. The output side is isolated from the controller, so any camera with a wired remote port can be used without a ground connection. The sequence is: close focus, close shutter (bulb opens), draw, blank, open shutter (bulb closes), open focus.

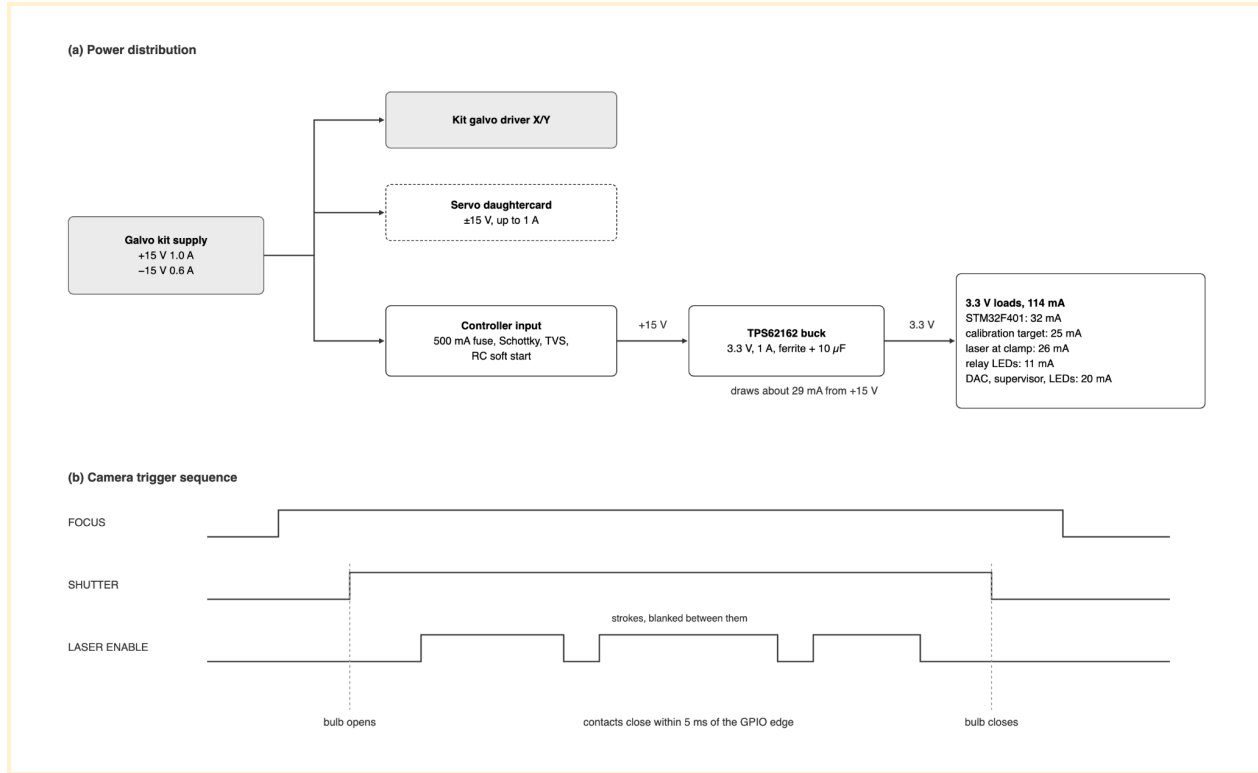


Figure 8: Power distribution and camera-trigger timing

Table 7: Camera Trigger and Power Requirements and Verification

Requirements	Verification
The 3.3 V rail stays at $3.30 \text{ V} \pm 3\%$ from no load to 400 mA.	- Connect an electronic load to the 3.3 V test point. - Sweep the load from 0 to 400 mA in 50 mA steps and record the DMM reading at each step. - Confirm every reading is between 3.20 and 3.40 V.
3.3 V ripple is below 20 mV peak-to-peak at full load.	- Set the load to 400 mA. - Measure the rail with the oscilloscope at a 20 MHz bandwidth limit using a tip-and-barrel probe. - Confirm peak-to-peak ripple is below 20 mV.
A reversed input causes no damage and draws under 1 mA.	- Apply -15 V from a bench supply with a 100 mA limit. - Confirm the supply reads under 1 mA. - Restore correct polarity and confirm the 3.3 V rail is normal.

Relay contacts close within 5 ms of the GPIO edge.	• Pull the relay output up to 3.3 V through 10 kΩ. • Capture the GPIO and the contact voltage on the oscilloscope. • Confirm the delay is under 5 ms on 10 of 10 trials.
The shutter opens before the first lit point and closes after the last on 10 of 10 runs.	• Capture the shutter line and laser enable on the oscilloscope while drawing a file. • Confirm the shutter closure precedes the first enable and its release follows the last blank on all 10 runs.

2.3.6 Optomechanics and Mounts

The open-bench optomechanical layout fixes the geometry used by calibration: the optical plate and target board sit on locked tripods, share an 800 mm beam-axis height, and remain 1000 mm apart as shown in Figure 3. The bonded ND filter and hardware current clamp maintain the Class 2 board-power limit; there is no enclosing box or lid.

Table 8: Optomechanics Requirements and Verification

Requirements	Verification
The galvo-pivot-to-board distance is 1000 ± 20 mm and the locked tripods hold the relative position within 0.5 mm over one hour.	• Measure the distance with a tape measure at assembly and confirm 1000 ± 20 mm. • Record the board-center position with the calibration fine sweep every 5 minutes for one hour; confirm total movement is under 0.5 mm.
The full commanded field terminates on the target board with at least 100 mm of margin.	• Draw the outer boundary of the field and measure from the drawn boundary to each board edge; confirm at least 100 mm of margin.
The bonded ND filter remains fixed in the optical path.	• Inspect the filter mount and confirm removal requires a screwdriver or hex key.

2.4 Software Design

The firmware is a state machine. Opening the arm switch or a stop command over USB blanks the laser and returns to IDLE from every state.

- **IDLE:** laser blanked, shutter released, waiting for a command over USB.
- **LOAD:** receive a stroke file, apply the inverse correction to every vertex, and compute the per-sample power command from the commanded velocity.
- **CALIBRATE:** for each of the four panel offsets, find each aperture with a coarse raster, run crossed fine sweeps in both directions, fit the inverse polynomial by least squares, and store the coefficients in flash.
- **ARMED:** wait until the arm switch is on.
- **DRAW:** re-measure the center fiducial position from the last calibration, close focus and shutter, stream the file at 50 kHz with blanking between strokes, blank, and release the shutter.

On the laptop, a Python script converts SVG paths into strokes resampled for a constant 100 mm/s board speed, with a deceleration and a short blanked dwell at each sharp corner.

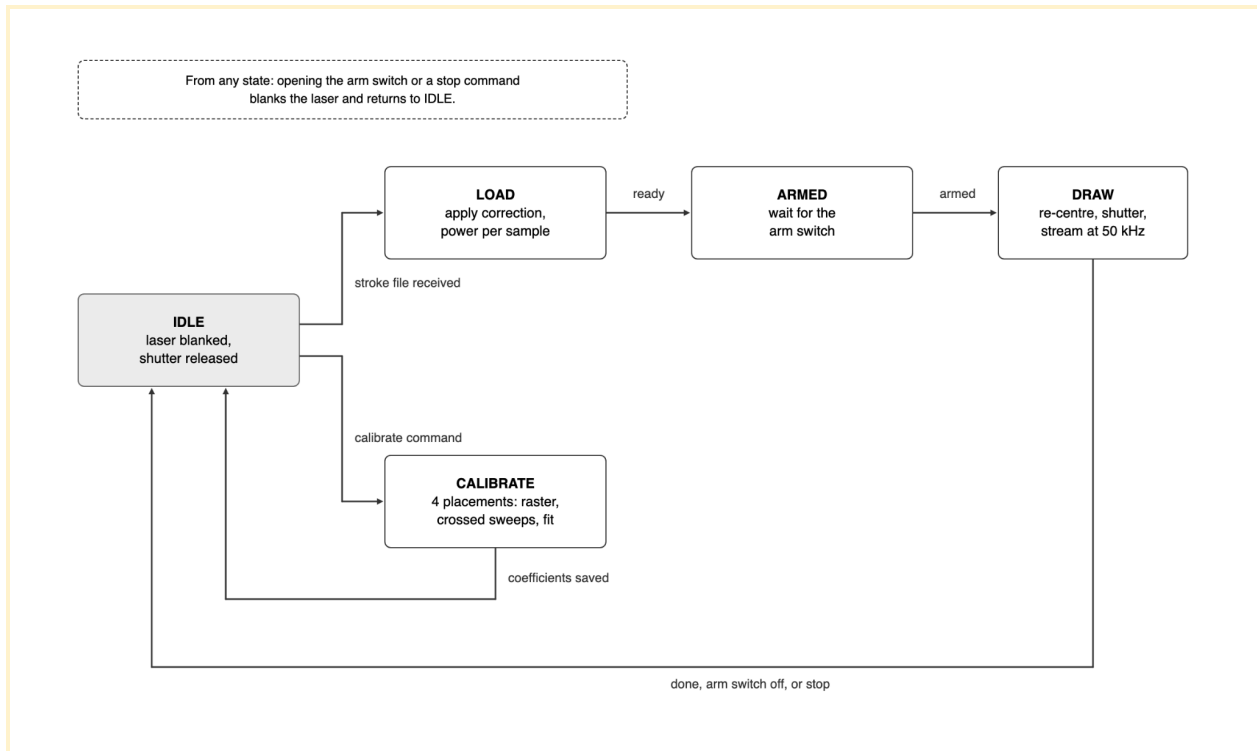


Figure 9: Firmware state flowchart

2.5 Tolerance Analysis

The interface most critical to success is the calibration target and correction fit, because HLR 1 and HLR 3 depend on it and every other subsystem's error lands there. We modeled the chain in a Monte Carlo simulation (sim/calibration/calibration_sim.py). Each trial draws a random system: galvo gain error (5%,

1 σ per axis), angle offset (0.3 degrees), throw distance (20 mm), board tilt (1.5 degrees), axis rotation (1 degree) and skew (0.5 degrees), two-mirror pincushion distortion (10 mm mirror spacing), 0.1 mm aperture position error, 0.1 mm registration error per placement, 0.008 mm sensing error after bidirectional averaging, 30 μ rad beam jitter, and linear thermal drift. Galvo lag is left out because sweeping each aperture in both directions cancels it. The fit uses the nominal aperture positions, as the firmware will. The fitted correction is checked on 81 held-out checkerboard points with 0.2 mm photograph measurement noise, and the uncorrected baseline aims with the nominal galvo scale. Table 9 summarizes 500 trials per configuration; drift is 0.1 mm/min unless noted, and pass means both HLR 1 and HLR 3 are met.

Table 9: Simulated calibration accuracy (500 random systems per row)

Configuration	RMS error, median / 95th (mm)	Max error, median / 95th (mm)	RMS reduction (median)	Pass rate
Uncorrected	12.19 / 20.43	22.68 / 38.56	n/a	0%
Degree 2, 1 placement (9 fiducials)	2.48 / 2.70	7.10 / 8.06	80%	1%
Degree 2, 4 placements (36 fiducials)	1.60 / 1.71	3.26 / 3.86	87%	99%
Degree 3, 4 placements (36 fiducials)	1.00 / 1.10	1.64 / 1.89	92%	100%
Degree 2, 4 placements, drift 0.5 mm/min	4.88 / 5.02	7.66 / 9.10	60%	0%
Degree 3, 4 placements, drift 0.5 mm/min	4.74 / 4.85	6.73 / 7.07	62%	0%
Degree 3, 4	0.38 / 0.45	0.82 / 1.03	97%	100%

placements, center re-check, 0.1 mm/min				
Degree 3, 4 placements, center re-check, 0.5 mm/min	1.16 / 1.25	2.25 / 2.53	90%	100%

The correction is a least-squares inverse polynomial from board position (x, y) to command (u, v). For degree 3 each axis has 10 coefficients:

$$u = \sum_{i+j \leq 3} a_{ij} x^i y^j, \quad v = \sum_{i+j \leq 3} b_{ij} x^i y^j \quad (9)$$

The results lead to four conclusions:

1. Sensing is not the limiting factor. The 0.008 mm sensing error and 0.011 mm DAC step are far below every other term.
2. Model order matters. The degree-2 map passes, but its 95th-percentile maximum error of 3.9 mm uses most of the 6 mm budget. The degree-3 map, fit to 36 fiducials (72 equations for 20 unknowns, condition number about 11), cuts that to 1.9 mm at no hardware cost.
3. All four panel placements are required. With one placement the median maximum error is 7.1 mm and almost every trial fails.
4. Thermal drift is the remaining risk. Drift that builds up between calibration and drawing shifts the whole image, and at 0.5 mm/min every trial fails even with the degree-3 map. Re-measuring the center fiducial just before drawing and removing that shift brings the pass rate back to 100% at 0.5 mm/min, so the DRAW state does this every time. After a 15-minute warm-up we also park the beam on one aperture and log its center every 30 s for 10 minutes to measure the real drift rate.

2.6 Risk Analysis

The laser driver carries the most safety risk, because a fault there could expose a person to a higher-power beam. Two passive limits address it: the bonded ND filter limits power optically, and the divider clamp limits current regardless of firmware. Neither can fail toward higher power, and the arm switch keeps the beam off until an operator enables it. The servo daughtercard carries the most schedule risk, because the galvo plant is undocumented; the go/no-go at the progress demo and the kit-amplifier fallback keep it off the critical path. Calibration accuracy carries the most technical risk to the high-level requirements, and Section 2.5 shows it has margin with a degree-3 fit and a center re-check before each drawing.

3 Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor

Illinois electrical engineering graduates reported an average starting salary of \$87,429 in 2024-25 [17], which is \$42 per hour over 2,080 working hours. We assume 150 hours per person, about 10 hours a week for 15 weeks.

Table 10: Labor cost

Team member	Rate (\$/hour)	Hours	Rate $\times$ 2.5 $\times$ hours
Alex Chen	42	150	\$15,750
Billy Huang	42	150	\$15,750
Michael Shi	42	150	\$15,750
Total		450	\$47,250

3.1.2 Parts

Prices are DigiKey single-unit prices checked in late September 2026. Parts marked E-Shop are supplied free by the ECE Electronics Services Shop; the listed cost is the distributor price where one exists.

Table 11: Parts list

Description	Manufacturer	Part #	Qty	Cost
Microcontroller (E-Shop)	STMicroelectronics	STM32F401RBT6	1	\$6.39
Development board	STMicroelectronics	NUCLEO-F401RE	1	\$19.07
Dual 16-bit DAC	Texas Instruments	DAC8562SDGSR	1	\$12.47
Dual op amp (level shift, servo)	Texas Instruments	OPA2197ID	4	\$15.92

Op amp (laser current loop)	Texas Instruments	OPA197IDR	1	\$2.10
Dual op amp, target TIA (E-Shop)	Texas Instruments	LMV922MX	5	E-Shop stock; obsolete at DigiKey
Dual comparator, target (E-Shop)	onsemi	LM393DR2	5	\$0.90
Current-sense amplifier	Texas Instruments	INA240A2D	1	\$3.78
3.3 V buck regulator	Texas Instruments	TPS62162DSGR	1	\$1.86
Supervisor	Texas Instruments	TPS3823-33DBVR	1	\$1.46
PhotoMOS relay	Panasonic	AQY212EH	2	\$3.68
N-channel MOSFET (E-Shop)	onsemi	2N7002MTF	3	E-Shop
Power BJTs	STMicroelectronics	TIP41C, TIP42C	1 each	\$3.83
Laser diode (one spare)	ROHM	RLD65MZT7-00A	2	\$35.80
Photodiode (three spare)	Vishay	BPW34	12	\$11.57
Threshold trimmer, 1 k Ω (one spare)	Bourns	3386P-1-102LF	2	\$3.70
Collimator housing and OD 0.7 ND filter	various	TBD	1 set	\$40.00 (estimate)
Passives, IDC	E-Shop and	various	lot	\$20.00 (estimate)

connectors, TO-220 heatsinks, 78L05, 8 MHz crystal	various			
PCBs (target, controller, daughtercard)	ECE 445 PCBWay orders	n/a	3	\$0.00
Galvo set: X/Y scanners, mirrors, driver board, show card, mount, ± 15 V supply, cables	Wonsung (wonsungstore)	Amazon B011ZPMUPO	1	\$109.99
Optical plate, board mounts, black acrylic panel, red acrylic filters, 9 printed holders	Makerspace	n/a	1	\$40.00 (estimate)
Parts subtotal				\$332.52

Machine shop: the optical plate and galvo mount, estimated at 4 hours; quote pending. The calibration panel is laser cut at the makerspace instead of machined.

3.1.3 Grand Total

The parts subtotal is \$332.52. Adding 5% shipping (\$16.63) and 10% sales tax (\$33.25) gives \$382.40. With \$47,250 in labor, the total project cost is \$47,632.40. The course provides \$50 per student, \$150 for the team; the galvo kit, mechanical parts, and any overage are personal purchases.

3.2 Schedule

Table 12: Weekly schedule and task assignments

Week of	Alex	Billy	Michael
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Oct 5 (design review; PCB round 2)	Bench the galvo kit: scale in degrees per volt, position node, coil R and L, swept-sine resonance	Breadboard the laser driver; power meter setup	Controller schematic (MCU, crystal, DAC, level shift)
Oct 12 (breadboard demo; PCB round 3)	Compensator values from the measured plant	Assemble the target board (ordered round 1); bring-up per its README	Controller layout; submit in round 3; DAC streaming on the Nucleo
Oct 19	Daughtercard schematic and layout	Panel and holders; first fiducial sweeps on the Nucleo	USB stroke loading; capture firmware
Oct 26 (PCB round 4)	Submit daughtercard; breadboard the servo loop on one axis	Set the clamp; measure board power with and without the filter	Assemble the controller PCB
Nov 2 (progress demo)	Servo go/no-go; build the optical plate and board stand	Velocity compensation constants from RAW tests	Degree-3 calibration fit and center re-check in firmware
Nov 9	Daughtercard assembly; step and hold tests	Exposure uniformity tests from RAW photographs	Camera sequence; SVG pipeline
Nov 16 (mock demo)	Integrate optics and mounts	Calibration accuracy tests (HLR 1, HLR 3)	Mock demo; firmware fixes
Nov 23	Fall break; buffer	Fall break; buffer	Fall break; buffer
Nov 30	Final demo and presentation	Final demo and presentation	Final demo and presentation
Dec 7	Final paper	Final paper	Final paper

4 Ethics, Safety, and Societal Impact

4.1 Societal, Economic, Environmental, and Global Impact

The instrument is aimed at hobbyists and photographers. Light painting now depends on a steady hand and trial and error; a repeatable calibrated tool lowers that barrier the way CNC machines opened fabrication to people without machinist training. We build around an off-the-shelf galvo kit instead of custom optomechanics, while adding closed-loop calibration. Power draw is a few watts for the electronics and tens of watts for the galvo amplifiers, the hardware is designed to be repaired and reused, and the laser diode is field replaceable. The calibration method applies to other open-loop beam-steering systems. The device has no network connection and collects no data.

4.2 Engineering Standards

Table 13: Applicable standards

Standard	How it applies
IEC 60825-1 [18], ANSI Z136.1 [19]	Laser classification: accessible board power is held below 0.50 mW at 659 nm through a bonded ND filter and a hardware clamp, inside the 1 mW Class 2 limit
ILDA ISP-DB25 [20]	Galvo command interface: ± 5 V differential X/Y
IPC-2221 [21]	Trace width and clearance for ± 15 V and 1 A coil current on the daughtercard
IEC 61010-1 [22]	Fusing, and keeping mains wiring inside the kit supply's enclosed terminal block
USB 2.0 [23]	Laptop-to-controller link (full-speed CDC)

4.3 Ethics

The IEEE Code of Ethics puts the safety, health, and welfare of the public first and asks engineers to disclose factors that could endanger people or the environment [24]. A laser projector tests that directly. Even a Class 2 laser relies on the blink reflex rather than being eye safe on its own, and that assumption fails if a fault raises beam power. We therefore limit power with parts that do not depend on software: a

current clamp set by a resistor divider that firmware cannot override, and a bonded ND filter. The beam is off until an operator closes the arm switch, and the firmware clamps every command to the calibrated window so a bad stroke file cannot walk the beam off the board.

We also considered misuse. Anyone who can steer a visible laser precisely could aim it at aircraft, vehicles, or people, which is illegal and dangerous whatever the laser's class. We cannot stop someone determined to modify the hardware, but the open-bench layout keeps the beam terminated on the designated board and the Class 2 ceiling reduces risk. We will report measured optical power and any requirement we miss, including a daughtercard fallback.

4.4 Safety

- **At 1 mW or less accessible emission at 659 nm, the finished product is Class 2 under IEC 60825-1 and ANSI Z136.1 [18], [19]. The Figure 3 configuration holds board power below 0.50 mW. Bring-up is different: before the ND filter is installed, the bare diode can emit up to 5 mW, which is Class 3R. Other hazards are the mains-powered kit supply, whose AC input is a screw terminal block that needs a properly strain-relieved, fused cord, daughtercard heatsinks that can reach 70 °C, and thin glass galvo mirrors that can chip if struck.**

4.5 Safety Procedures

- All three team members complete the Division of Research Safety laser safety training (OVCR training library) and the ECE 445 laboratory safety training before touching the laser, and give the certificates to the TA [25], [26].
- Any work with the ND filter removed uses OD 2 or better glasses at 659 nm for everyone present, with the beam below eye level and a warning sign posted.
- The current clamp and the arm switch are verified (Table 4) before any drawing.
- No one works alone on the powered system, and the arm switch stays with the person running the test.
- The kit supply is wired with a fused, strain-relieved mains cord and checked by the TA before first use; until then the galvos run from a ± 15 V bench supply. No other changes are made to the mains side.
- Heatsinks are labeled, and the daughtercard is mounted where it cannot be touched during

operation.

A laser bring-up checklist and a power-measurement log will be kept with the lab notebook and shown at the demo.

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