

# Self-Calibrating Long-Exposure Laser Light Painter

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## 1. Introduction

### 1.1 Problem

Long-exposure light painting is normally 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 people build these projects around never actually measure their own output. Two errors show up clearly in the photograph. The mirror geometry and sensor scale distort the image geometrically, and the beam slows at corners and speeds up along straight segments, so exposure is uneven across a stroke. The camera integrates every one of these errors over the length of the exposure, so what shows up in the photo is bent lines, bright blobs where the beam lingered, and strokes that fade out where it moved too fast.

Hobby laser projectors are routinely built by people with no laser safety training, and an unmonitored beam is the failure mode behind laser strikes on aircraft. Pilots reported 10,994 strikes to the FAA in 2025, down from 12,840 the year before but still high enough that the agency runs a standing awareness campaign. A system that measures where its beam actually lands, and cuts the laser in hardware when the measurement stops making sense, is a more defensible design than an open loop command path that no sensor ever checks.

### 1.2 Solution

We are building a laser light painting instrument around a custom controller PCB. A pair of closed loop galvos steer a 650 nm laser onto a white target board standing 1 m away in a darkened room, while a DSLR positioned beside the optical head holds its shutter open. The controller measures where the beam actually lands using a removable photodiode calibration target that mounts on the face of that board, fits a two dimensional geometric correction from the measurements, and adjusts laser current with beam velocity so a stroke receives roughly even exposure along its length.

The two axis demo runs on the galvo kit's own amplifiers. Alongside that we are designing and characterizing one custom galvo servo daughtercard: loop compensation, current sensing, a bipolar power stage, closing the loop on one axis using the position signal the kit driver already produces. The kit driver has an output link that works as a hardware selector. Pull it and the kit can no longer drive that coil, so the daughtercard takes over and the two can never fight over the same coil.

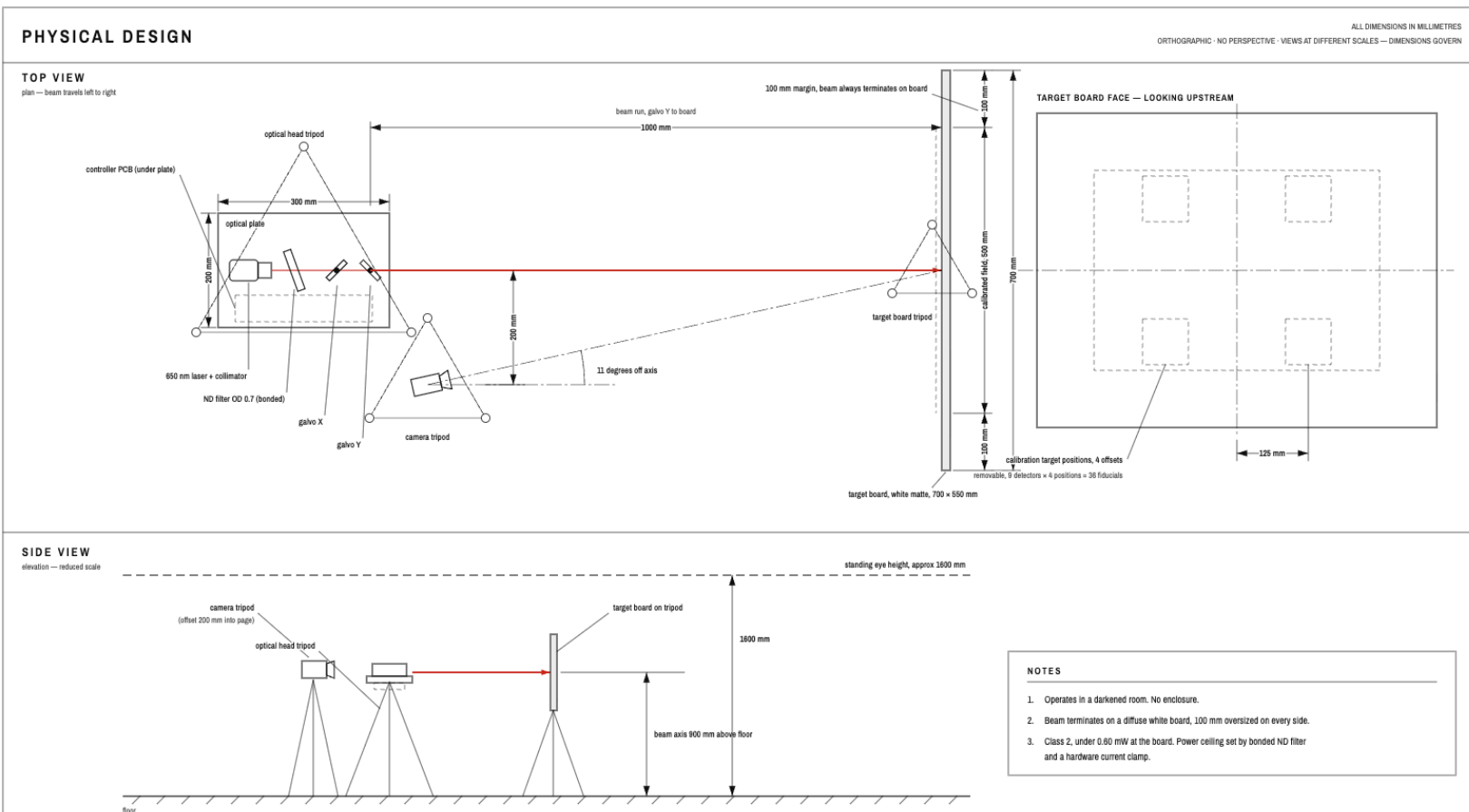
If time allows: a small learned residual model trained on recorded trajectories, correcting whatever the static calibration misses, trained on a laptop with inference bounded enough to run on the microcontroller. After that, a second custom servo channel. After that, drawing to music.

### 1.3 Visual Aid

## 1.4 High-level Requirements List

- 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 that were 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.
- The hardware safety interlock drops the laser diode current below its lasing threshold within 10 ms of any of: a stalled beam (no perimeter detector crossing within 250 ms while the laser is enabled), an out-of-zone command (either DAC output outside the calibrated field window), an open enclosure lid, a disarmed key switch, or a lost controller heartbeat. The interlock latches and clears only through the key switch, and operates with the controller unpowered.

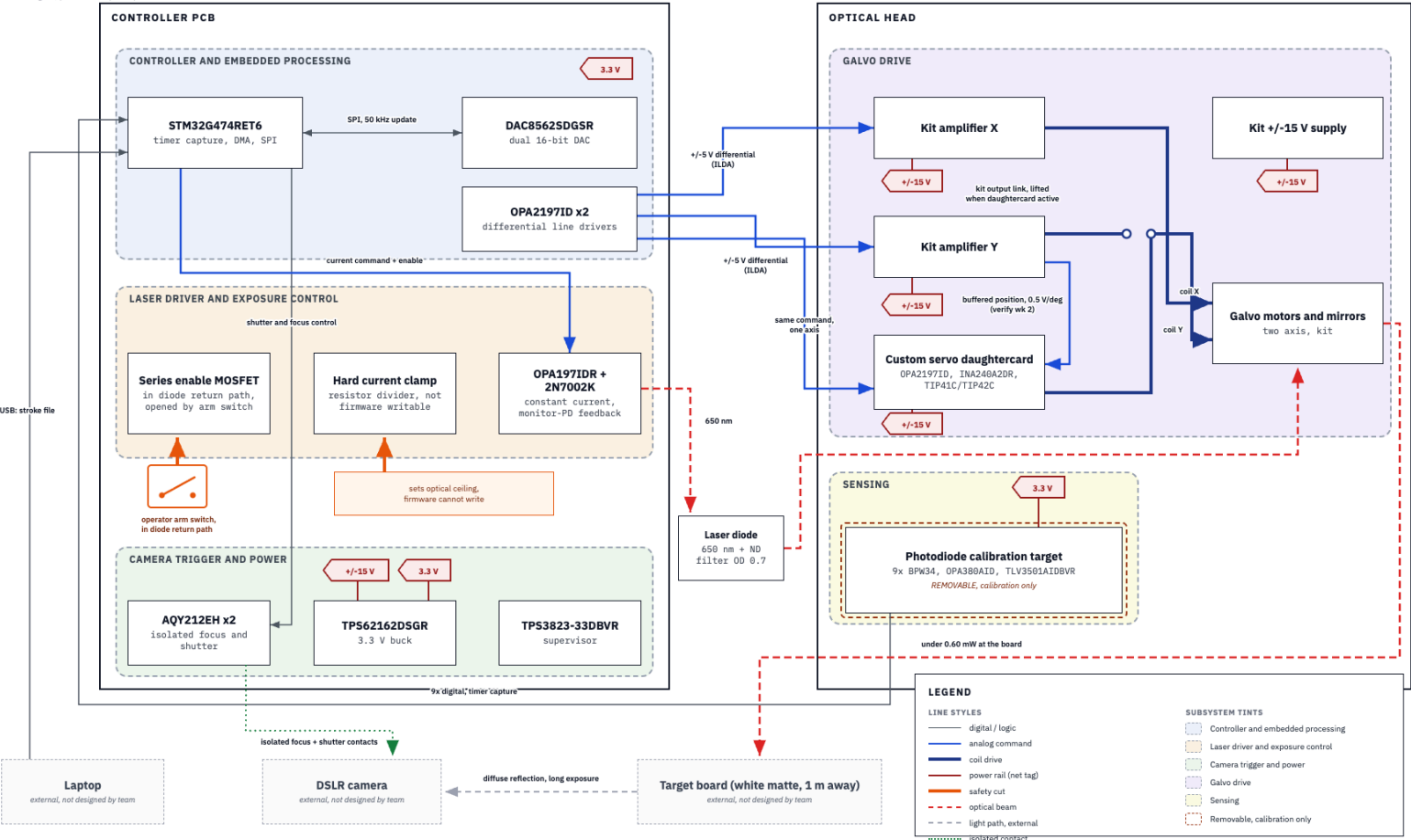
## 2. Design



2.1 Block Diagram

Laser galvo projector — system block diagram

Rev A - signal, power and optical paths



## 2.2 Subsystem Overview

| Subsystem                          | Function                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Key parts                                               |
|------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------|
| Controller and embedded processing | An STM32G474RET6 reads a stroke file over USB from the laptop, applies the stored geometric correction to every vertex, and streams the corrected X and Y pair to a DAC8562SDGSR over SPI at a fixed update rate set by a hardware timer and DMA. An OPA2197ID pair converts each DAC output into the ILDA-standard differential command, plus or minus 5 V per axis into the 200 kOhm galvo amplifier inputs. The same firmware sets the laser current command, asserts the laser enable line, drives the two camera relays, and toggles a heartbeat line into the interlock. It receives nine digital lines from the calibration target into timer capture inputs. This subsystem is what makes HLR1 achievable, because the correction is applied here, and it is a dependency of HLR3, because a stopped controller must stop toggling the heartbeat. | STM32G474RET6, DAC8562SDGSR, OPA2197ID, TPS3823-33DBVR  |
| Photodiode calibration target      | Nine BPW34 photodiodes sit behind 1 mm apertures and 650 nm bandpass filters at positions held to plus or minus 0.1 mm by the PCB artwork. Each channel is an OPA380AID transimpedance amplifier followed by a TLV3501AIDBVR comparator whose threshold is set relative to the measured ambient floor. When the beam sweeps across an aperture the comparator produces a pulse; the controller timestamps both edges in timer capture and takes the midpoint as the beam center for that fiducial, then repeats the sweep in the opposite direction and averages to cancel comparator delay. The board mounts on registration pins at four known offsets on the screen frame,                                                                                                                                                                             | 9x BPW34, 9x OPA380AID, 9x TLV3501AIDBVR, 650nm filters |

| Subsystem                                        | Function                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Key parts                                                                 |
|--------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
|                                                  | <p>giving 36 fiducials. This subsystem exists to serve HLR1 and HLR3: it is the only measurement of where the beam actually lands, and the before-and-after comparison that HLR3 scores comes from the same data. It hands the controller nine digital lines and nothing else. It is removed before drawing.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                           |
| <p>Laser driver, exposure control, interlock</p> | <p>A constant-current sink built from an OPA197IDR error amplifier, a 2N7002K MOSFET, and a sense resistor drives an RLD65MZT7 650 nm diode, with the diode's own monitor photodiode closing the loop so optical output tracks the command rather than the current alone. The current command arrives from the controller as an analog level and follows <math>I = I_{\text{threshold}} + k \times \text{commanded beam velocity}</math>, so exposure per unit length stays constant; below a minimum velocity, and during retrace, the driver blanks. A resistor divider on the OPA197 reference hard-clamps the maximum current, and a fixed OD 0.7 neutral density filter in the optical path sets accessible emission. The series interlock MOSFET sits in this subsystem's current path and opens whenever the enclosure lid switch opens. This subsystem delivers HLR2 and holds the optical power ceiling that keeps the instrument in Class 2.</p> | <p>RLD65MZT7, OPA197IDR, 2N7002K, TLV1702AIDR, lid switch, key switch</p> |
| <p>Custom galvo servo daughtercard</p>           | <p>This card replaces one kit amplifier for one axis. It takes the same differential ILDA command from the controller and the buffered position output the kit driver already produces, nominally 0.5 V per degree optical, which we will verify on the bench in week 2. An OPA2197ID forms the position error, a second OPA2197ID stage provides lead-lag compensation with a notch</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <p>OPA2197ID, INA240A2DR, TIP41C/TIP42C</p>                               |

| Subsystem                            | Function                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Key parts                 |
|--------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|
|                                      | <p>near the first mirror resonance, and a complementary TIP41C and TIP42C class-AB output stage drives the coil from the kit's plus and minus 15 V rails. An INA240A2DR across a shunt provides current sense for a clamp that protects the coil. The kit driver's coil output link is physically lifted when the daughtercard is connected, so the two can never drive the same coil. This subsystem is a graded circuit-level design; it is not on the path to any high-level requirement, which is deliberate, because the two-axis image demonstration runs on the kit amplifiers regardless of how the daughtercard performs.</p>                                                                                                                                                                                                                                                                                                                                                                                                                        |                           |
| Camera trigger, power, and enclosure | <p>Two AQY212EH PhotoMOS relays present isolated dry contacts that imitate a wired camera remote's focus and shutter, so the controller can open the shutter, draw, blank, and close in a repeatable sequence with no electrical connection to the camera. The galvo kit's plus and minus 15 V linear supply feeds the kit amplifiers and the daughtercard; a TPS62162DSGR buck derives 3.3 V for the controller from the same input, with a TPS3823-33DBVR supervisor, fuses, soft start, and reverse polarity protection on the board. The optomechanics are a single rigid plate carrying the laser, its collimator, the fixed neutral density filter, and the galvo pair, plus a separate stand holding the target board. Rigidity is the requirement that matters here: the calibration is only valid while the plate and the board hold the geometry they had when the fit was taken, so both sit on locked tripods rather than anything adjustable by hand. This subsystem fixes the 1 m projection geometry that every number in HLR1 depends on.</p> | 2x AQY212EH, TPS62162DSGR |

## 2.3 Subsystem Requirements

#### Controller and embedded processing

- Update the X and Y command pair at a fixed 50 kHz sample rate with jitter under 200 ns, so a 100 mm/s stroke is sampled every 2 micrometres and timing jitter contributes under 0.02 micrometres of position error.
- Evaluate the stored per-axis polynomial correction for every vertex in under 20 microseconds, so correction never limits the sample rate.
- Capture comparator edges with a timer resolution of 10 ns or better (170 MHz timer clock gives 5.9 ns).
- Hold the laser enable line low at reset and during firmware update.

#### Photodiode calibration target

- Produce a comparator pulse of at least 5 ms width when the beam crosses an aperture at the 100 mm/s calibration sweep speed, which a 1 mm aperture gives by geometry.
- Maintain a signal-to-noise ratio at the comparator input of at least 40 dB with room lights on, achieved by the 650 nm bandpass filter and a baffle tube limiting acceptance angle.
- Hold photodiode centre positions to plus or minus 0.1 mm across the board, and repeat registration between the four mounting offsets to plus or minus 0.1 mm.
- Deliver all nine channels as 3.3 V logic into controller capture inputs.

#### Laser driver and exposure control

- Hold commanded optical output within plus or minus 5% of the current law over the range 2.0 mW to 3.0 mW at the diode, using monitor photodiode feedback.
- Hard-clamp diode current so that optical output at the diode cannot exceed 3.5 mW regardless of the commanded level, giving at most 0.70 mW accessible at the screen through the fixed OD 0.7 filter, with margin against the 1 mW Class 2 limit.
- Blank within 100 microseconds of the blanking command, so a 100 mm/s stroke overshoots a corner by under 0.01 mm.
- Reach steady optical output within 200 microseconds of unblanking.
- Drop diode current below lasing threshold within 10 ms of the enclosure lid switch opening, through a series MOSFET in the diode return path that does not depend on firmware.

#### Custom galvo servo daughtercard

- Settle a 10 degree optical step to within 2% in 5 ms or less.
- Hold a static commanded point within 1 mrad optical over 10 minutes after a 10 minute warm-up.
- Limit coil current to the kit driver's rated maximum, with the clamp active before the output stage saturates.
- Accept the same plus or minus 5 V differential command as the kit amplifier, with input impedance at least 100 kOhm.

#### Camera trigger, power, and enclosure

- Provide focus and shutter contacts with under 50 Ohm on-resistance and at least 1500 V isolation from controller ground.
- Hold the 3.3 V rail within plus or minus 3% with all subsystems active, including worst-case simultaneous laser, relay, and DAC load.
- Hold plus and minus 15 V rail ripple under 50 mV peak to peak in the 0 to 10 kHz band, since that band lands directly in the galvo servo passband.

- Hold the optical plate and target board fixed to within 0.5 mm of relative position over a one hour session, since 0.5 mm at 1 m is half the thermal drift term in the error budget.
- Terminate the full commanded field on the target board with at least 100 mm of margin on every side, so a commanded overshoot lands on the board rather than past it.
- Keep the beam axis horizontal at 900 mm above the floor, below standing eye height.

## 2.4 Tolerance Analysis

The real question here is whether the electronics are even precise enough for calibration to matter. If DAC quantization or command path noise were the dominant error, no amount of polynomial fitting would get us to 3 mm RMS, because you cannot calibrate away a limit that low in the signal chain. So before committing to the whole calibration approach, we ran the numbers.

The DAC8562SDGSR is 16 bit over a differential plus or minus 5V, 10V span, ILDA command. That gives a quantization step of 10V divided by 65536, about 152.6 microvolts per LSB. Using the galvo kit's published scale, about 20 degrees optical per 5V command channel, or 4 degrees per volt optical (we will re-measure this once the kit is actually in hand rather than trust the listing), one LSB works out to an optical angle step of roughly 6.1 times ten to the minus 4 degrees, or 1.07 times ten to the minus 5 radians. At the 1 m projection distance in the success criteria, that is a linear displacement on the screen of about 0.011 mm per LSB. That's about 300 times smaller than the 3 mm RMS target. DAC quantization is not going to be the bottleneck unless something in the analog path is adding hundreds of LSBs of noise, which a properly decoupled plus or minus 15V rail and the OPA2197 level shifters should not do. So the dominant error really is geometric: the tangent projection nonlinearity of two mirrors onto a flat screen, position scale gain error, axis skew and offset, all of which the degree two polynomial fit is built to capture. We learned the hard way on the CAD assignment that trusting a datasheet number instead of measuring it on the bench is how you end up debugging a phantom problem for a day, so this estimate gets rechecked against the real kit in week 2 before we build anything around it.

## 3. Ethics, Safety, and Societal Impact

### 3.1 Ethics

The IEEE Code of Ethics puts the safety, health, and welfare of the public above everything else, and asks engineers to disclose anything that could put people or the environment at risk. A laser projector is a direct test of that. Even a Class 2 laser depends on the human blink reflex rather than being eye safe on its own merits, and that assumption breaks if a fault raises beam power, if the beam stalls and dumps continuous exposure onto one point, or if someone pulls the ND filter. We built in several independent layers rather than one: the accessible power is clamped by a resistor divider that firmware cannot override, the ND filter sits fixed in the optical path where a user cannot remove it, and a latched hardware interlock, running independent of the controller, kills the laser on a stalled beam, an out of range command, an open lid, or a missing heartbeat. The laser being off is the default state, and firmware has to actively prove the system is safe to turn it on, rather than the other way around.

We also thought about misuse. Anyone who can steer a visible laser precisely can point it at aircraft, vehicles, or people, and that's illegal and dangerous no matter how the laser is classified. We cannot stop someone determined to defeat the interlock hardware. But this

design does not make that any easier than a laser pointer already sold at a gas station, and the enclosure, the low optical power at the screen (under 0.75 mW), and the Class 2 rating keep the finished product no more dangerous than the hobby projectors already on the market. If anything it is safer than most of them, because it measures its own output instead of just trusting an open loop driver.

## **3.2 Safety and Regulatory Standards**

IEC 60825-1 and ANSI Z136.1 govern laser hazard classification. At our operating point, 1 mW or less accessible emission at 650 nm, the finished enclosed product sits in Class 2, which does not require registering with UIUC's Division of Research Safety (that's only Class 3B and 4) and does not require safety eyewear during normal use. Bring up is different. Before the ND filter goes in permanently, the bare diode can put out up to 5 mW, which is Class 3R, so all three of us are completing the DRS Laser Safety module on top of the standard ECE 445 lab safety modules before touching the laser, and we're keeping OD 2 or better glasses at the bench for any work done with the filter out. We'll measure optical power directly with a calibrated power meter rather than inferring it from drive current, with and without the filter, at max commanded current, and cross check against a photodiode of known responsivity.

## **3.3 Societal, Economic, Environmental, and Global Impact**

This is aimed at hobbyists and photographers. Light painting right now depends on a steady hand and a lot of trial and error, and a repeatable calibrated tool lowers that barrier the same way a CNC machine opened up fabrication to people without machinist training.

On cost, we deliberately built around an off the shelf galvo kit (70 to 130 dollars) instead of custom optomechanics, so the total build lands in the same range as existing hobby laser projectors, 150 to 300 dollars, while adding closed loop calibration those products don't have. Power draw is low, a few watts for the laser and tens of watts for the galvo amps, and the enclosure is built to be reused and repaired rather than thrown away. The only real consumable is the laser diode itself, and it's field replaceable.

The calibration method, measure with a known fiducial target, fit a low order polynomial, apply it per vertex, generalizes to any open loop beam steering system. It's not tied to a particular market, and it doesn't touch a network or collect data, so there's nothing here that raises privacy or export control questions.