Automatic Laser Cavity Mirror Alignment and Beam Profiler System

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Project Motivation

- Manual Adjustment of Open Cavity Laser can be Frustrating and Time-Consuming

- Market Vacuum
  - No Affordable Options for Automatic Alignment
  - No Products Offering Profiling and Alignment

Overarching System Goals

I. Automatically Bring an Open Cavity Laser to Lasing and to Max Power

II. Provide a Visual Live-Feed of Information Regarding the Laser

III. Allow Attachment and Detachment to any Number of Different Laser Cavities

Major Design Constraints

- Ambient Light
  - Disrupts measurements and potentially creates false lasing flag
- Motor Vibration
  - Minute movements could impact the alignment of the laser

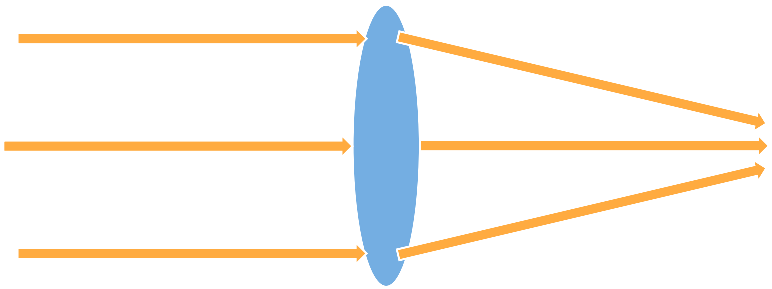
I. Automatic Lasing and Max Power

- Laser Power Meter
  - Photodiode
  - Focusing Lens
  - Transimpedance Amplifier
- Controls and Computing
  - Q-Learning
  - Threshold Approach
  - Maximum Power Approach

Photodiode: Osram BPX 61

- Price: $12.18
  - Low-cost
- Wavelength Range: 400nm-1100nm
  - Captures required spectral range
- Not our first choice
  - Long lead time necessitated this option

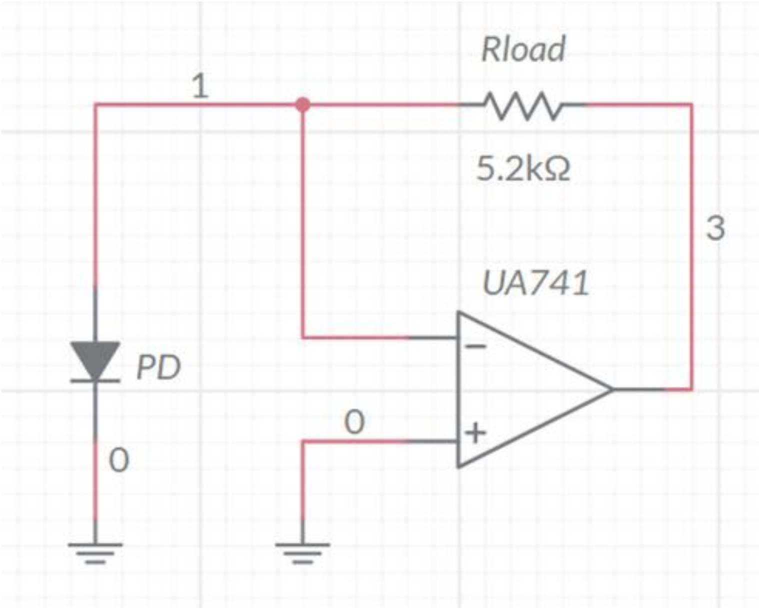
Focusing Lens



- Active area of the photodiode: 2.65x2.65mm
- Diameter of focusing lens: 12.7mm
- Focusing lens increases effective active area
- Amount of increase roughly equal to 18 times

Transimpedance Amplifier

- Configuration used to reduce noise
- Voltage reading across load resistor proportional to incident laser power
  - Informs motor movement



Motor Specifications

Motor Name	DS3218	FS90R
Type	Positional servo	Continuous servo
Weight (g)	60	9
Quantity	1	2
Max Torque (oz/in)	263.8 @ 5 V	18 @ 4.8 V
Max Torque (oz/in)	298.5 @ 6.8 V	21 @ 6 V
Max RPM	93.75 @ 5V	100 @ 4.8 V
Max RPM	107 @ 6.8 V	130 @ 6 V

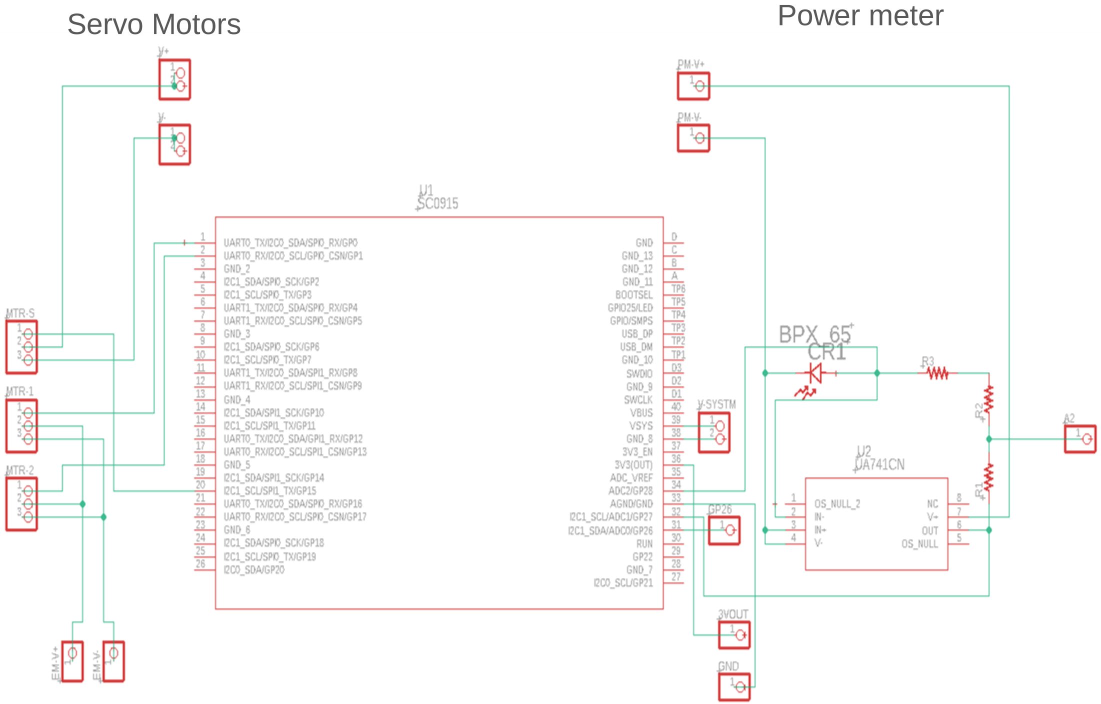
DS3218


FS90R

PCB Design

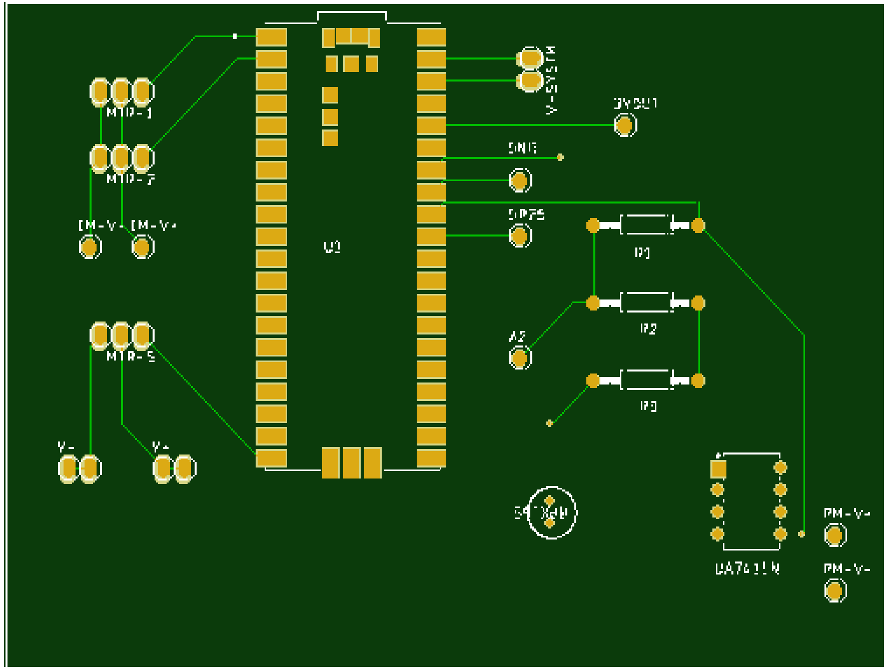
PCB Schematic

- Software: Autodesk Eagle
- Manufacturer: JLPCB
  - Based in China
  - 9 Day delivery
  - Has issues with payment

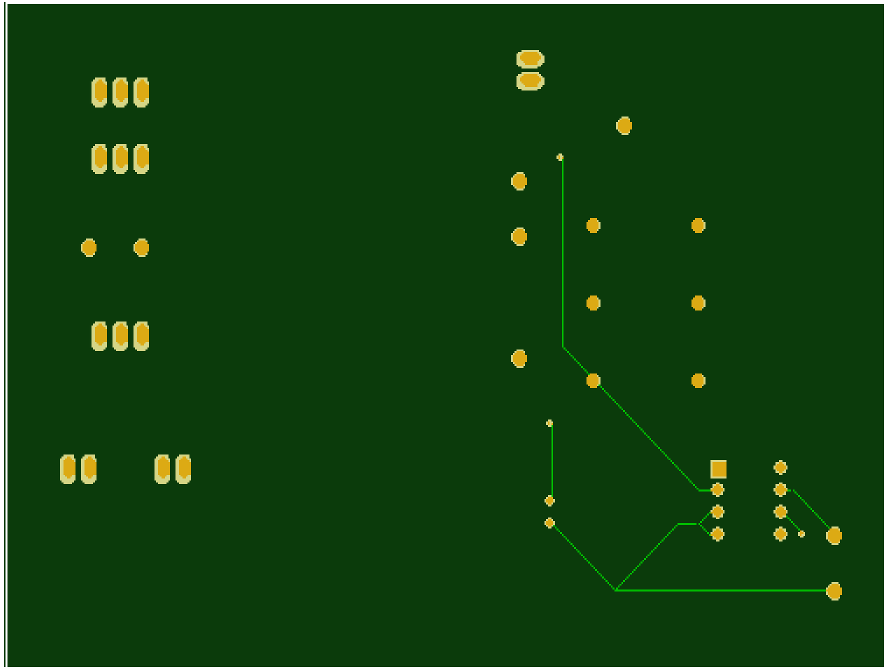


Final PCB product

Top

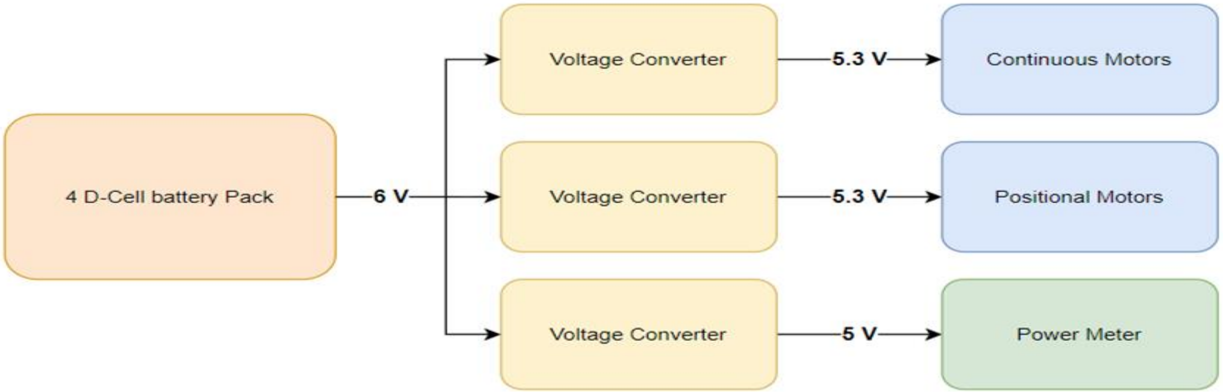


Bottom



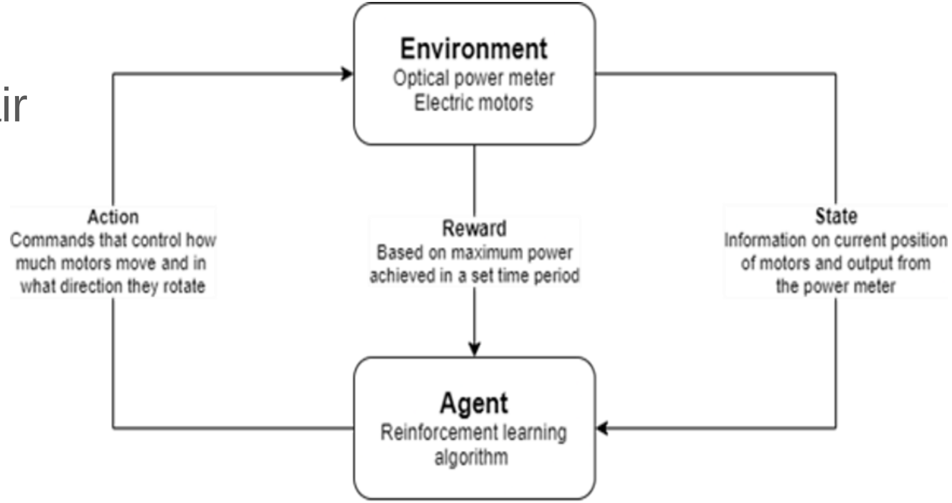
Power Supply Design

- Voltage supply: 6V battery pack(4xD-cell)
- Voltage converter: DC to DC step down voltage converter (3V-40V to 1.5V-35V)



Q-Learning Approach

1. Agent performs an action
2. Environment provides a reward
3. Agent associates the state action pair with that reward
4. Q values are updated based on reward
5. Cycle repeats for each training episode

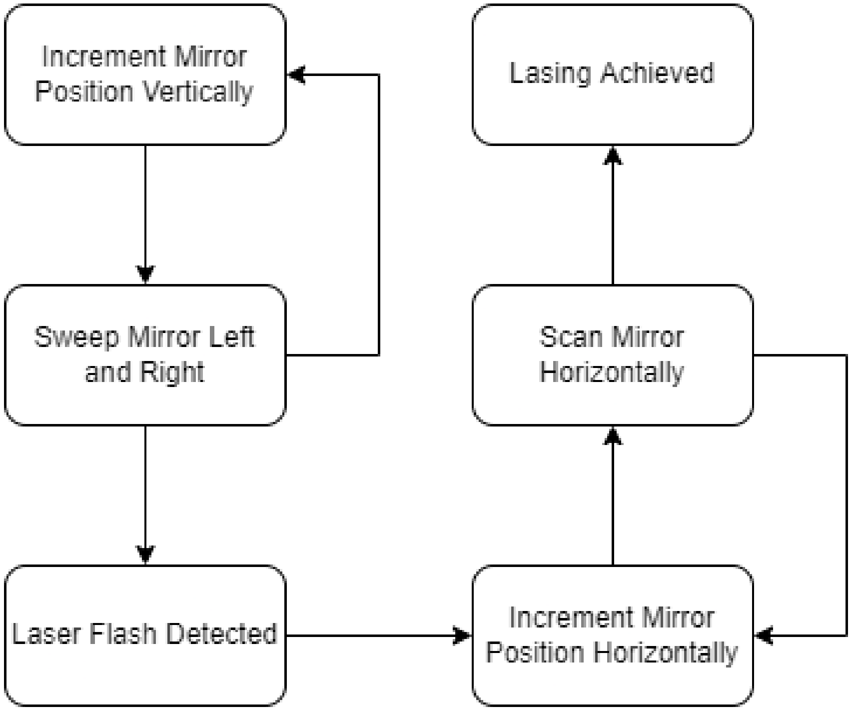


Difficulties with Q-Learning

- Running enough training episodes would take too long
- The output fluctuates at any given orientation
- The motors move at different speeds
- Any changes to environment invalidate previous data

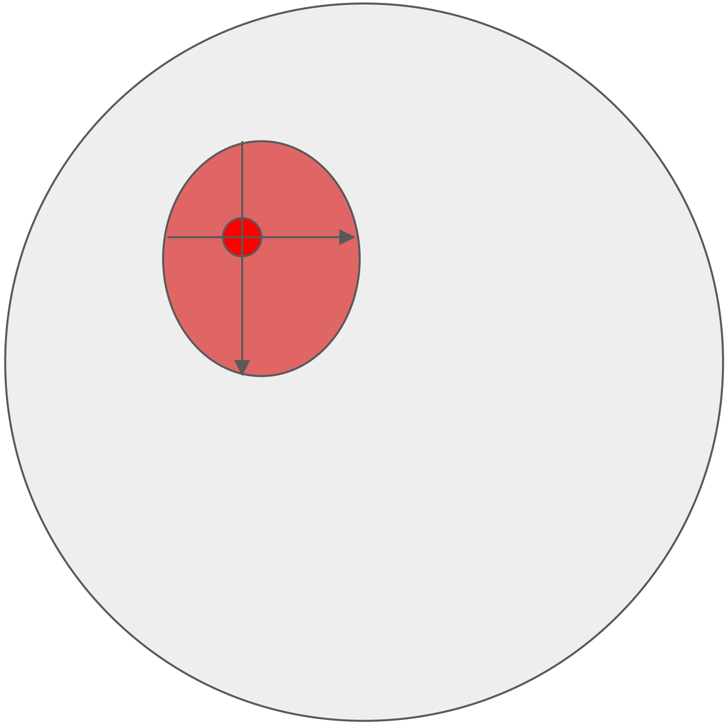
Threshold Search Approach

1. Continuous motor moves mirror vertically
2. Servo motor sweeps mirror horizontally looking for a flash
3. When a flash is detected the servo motor increments mirror horizontally
4. Other continuous motor scans horizontally
5. Adjustments stop when lasing threshold is met



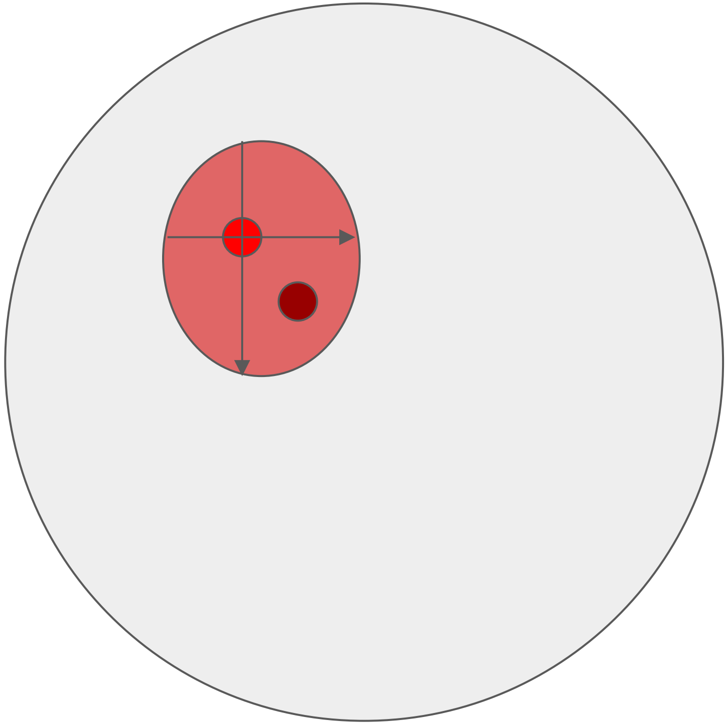
Maximum Power Approach

1. Start at a point of lasing
2. Search horizontally within lasing area for max power
3. Return to horizontal max power location
4. Search vertically within lasing area for max power
5. Return to vertical and horizontal max power location



Maximum Power Difficulties

- It is possible for there to be multiple local max power locations, and one may be larger than the other
- It is possible to “under shoot” the max power location when returning since motors could move at different speeds in different directions



II: Live-Feed of Laser

- Develop a Camera Based Beam Profiler
- Create a Graphical User Interface (GUI) to Visualize Profiler
- Have this GUI Perform Mathematical Operations to Determine Relevant Beam Parameters

Beam Profiler: Hardware

Raspberry Pi 4

Easy Integration with RP Camera

Large Library of Resources

Relatively Affordable

RP HQ Camera

Requires RP Computer

Camera Decision Matrix

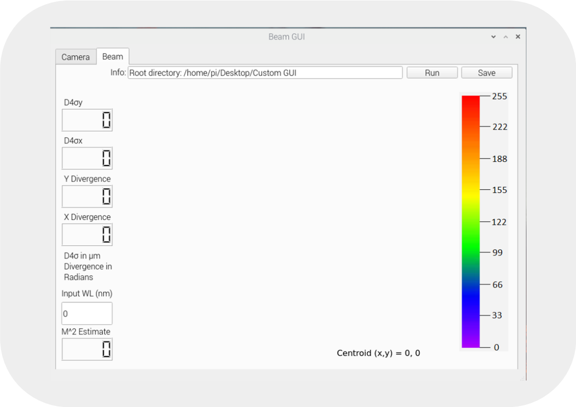
Camera	Manufacturer	Price ($)	Sensor Area (mm)	Pixel Size (um)	Resolution (MP)	FPS	
Basler Ace GigE	Basler	875	6.78x5.43	5.3x5.3	1.3	60	
RP HQ 12	Raspberry Pi	50	6.28x4.72	1.55x1.55	12.3	30	
ArduaCam 5	ArduCam	15	3.62x2.79	1.4x1.4	5	30	

Beam Profiler: Software

‘GUI’ Module

Primarily uses the PyQt5 Library

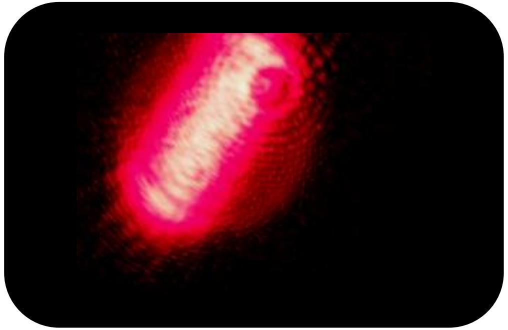
Creates Widgets that function as buttons, LCD numbers, and text entry areas within a defined window



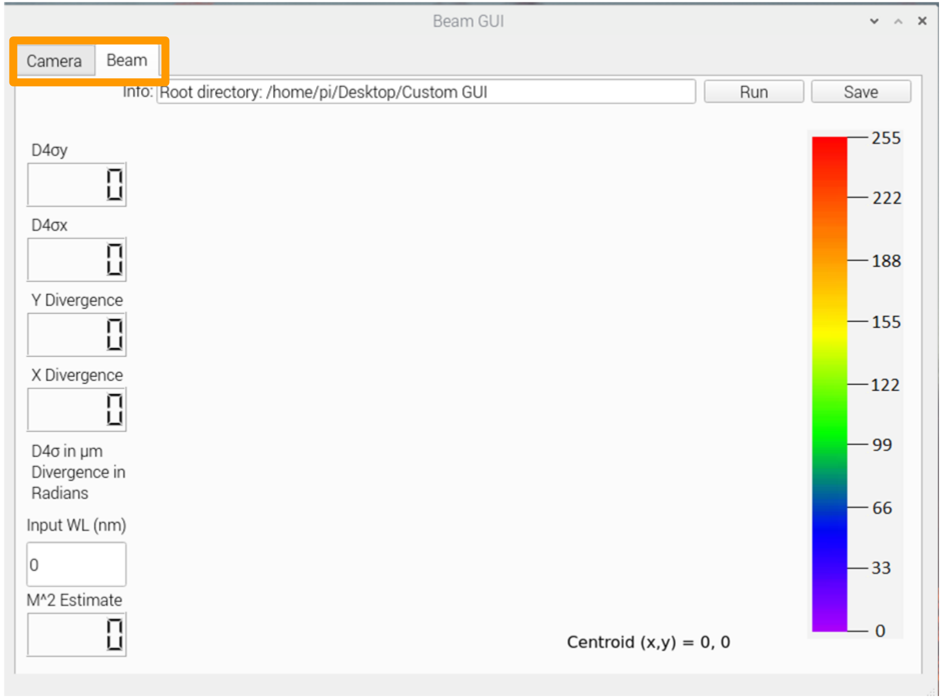
‘Camera’ Module

Makes use of CV Library

Displays feed from Pi HQCam and performs image processing

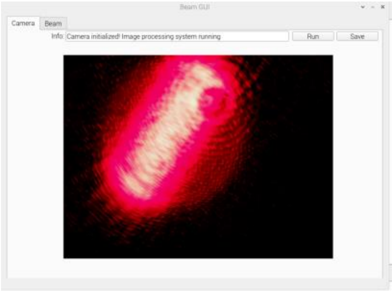


GUI Module Features

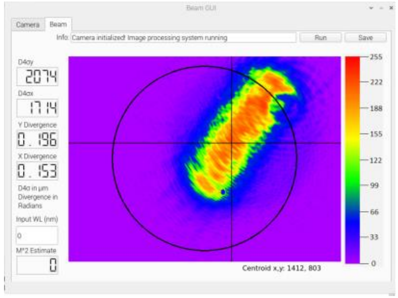


Beam and Camera Tabs

Switches between raw camera feed and color coded feed with parameter monitoring



‘Camera’



‘Beam’

GUI Module Features

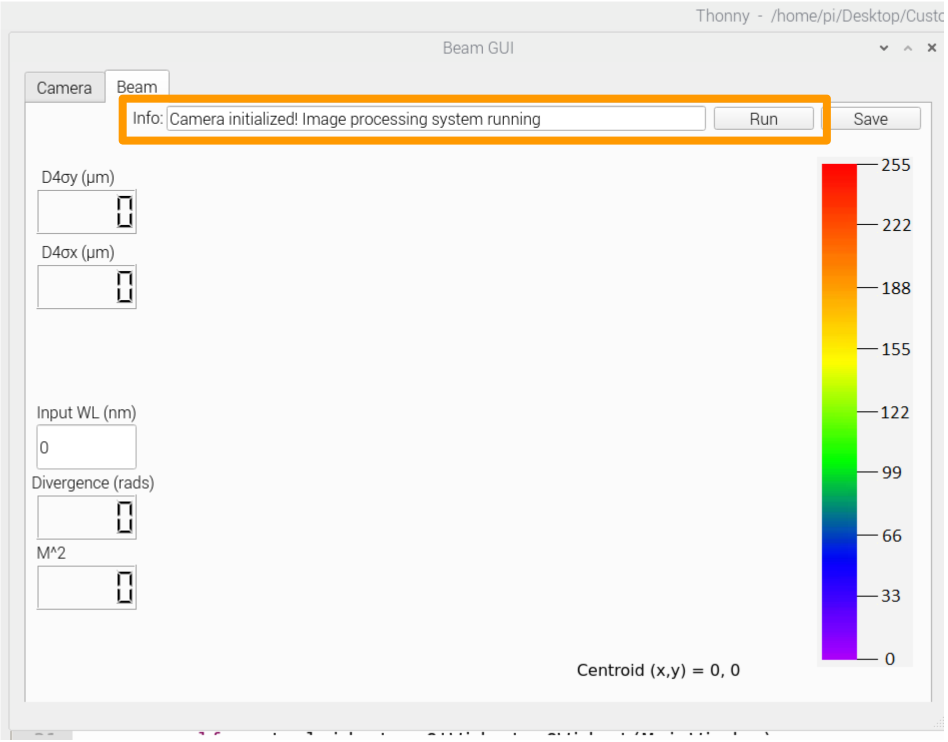
<u>Initialization Widgets</u>

'**Run**' Button

Initializes camera and starts image acquisition

'**Info:**' Text Box

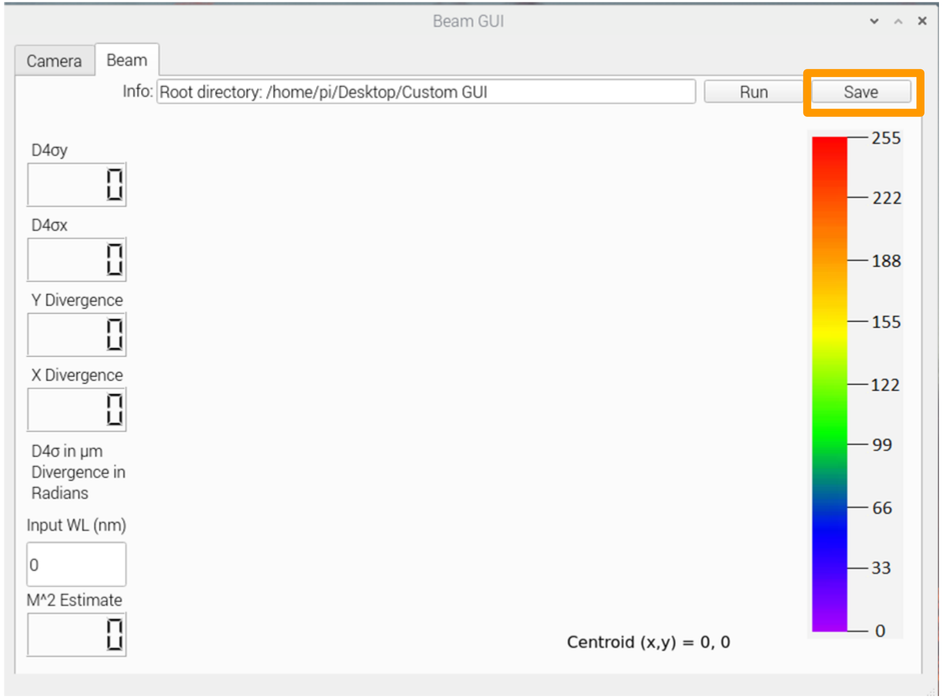
Prints information relating to the program operation



GUI Module Features

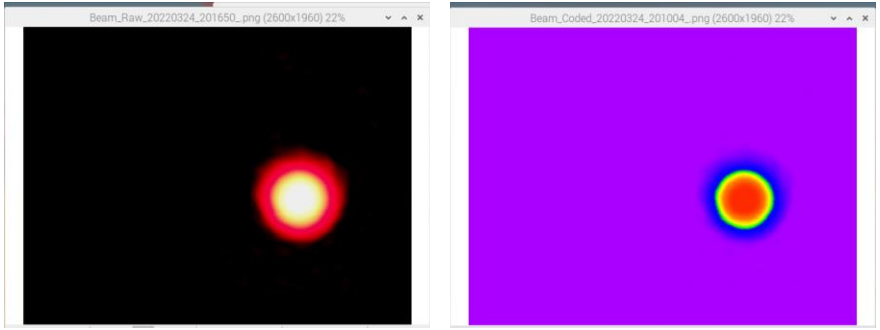
Save Button

Saves a variety of different files relating to the beam operation into a specified folder

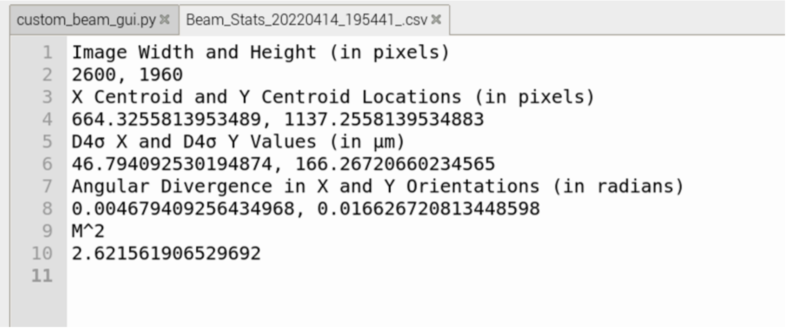


Save Button Continued

5 Different Files:

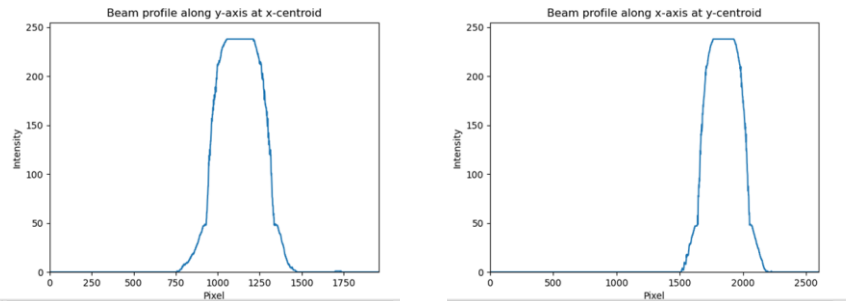


Beam Spot .pngs

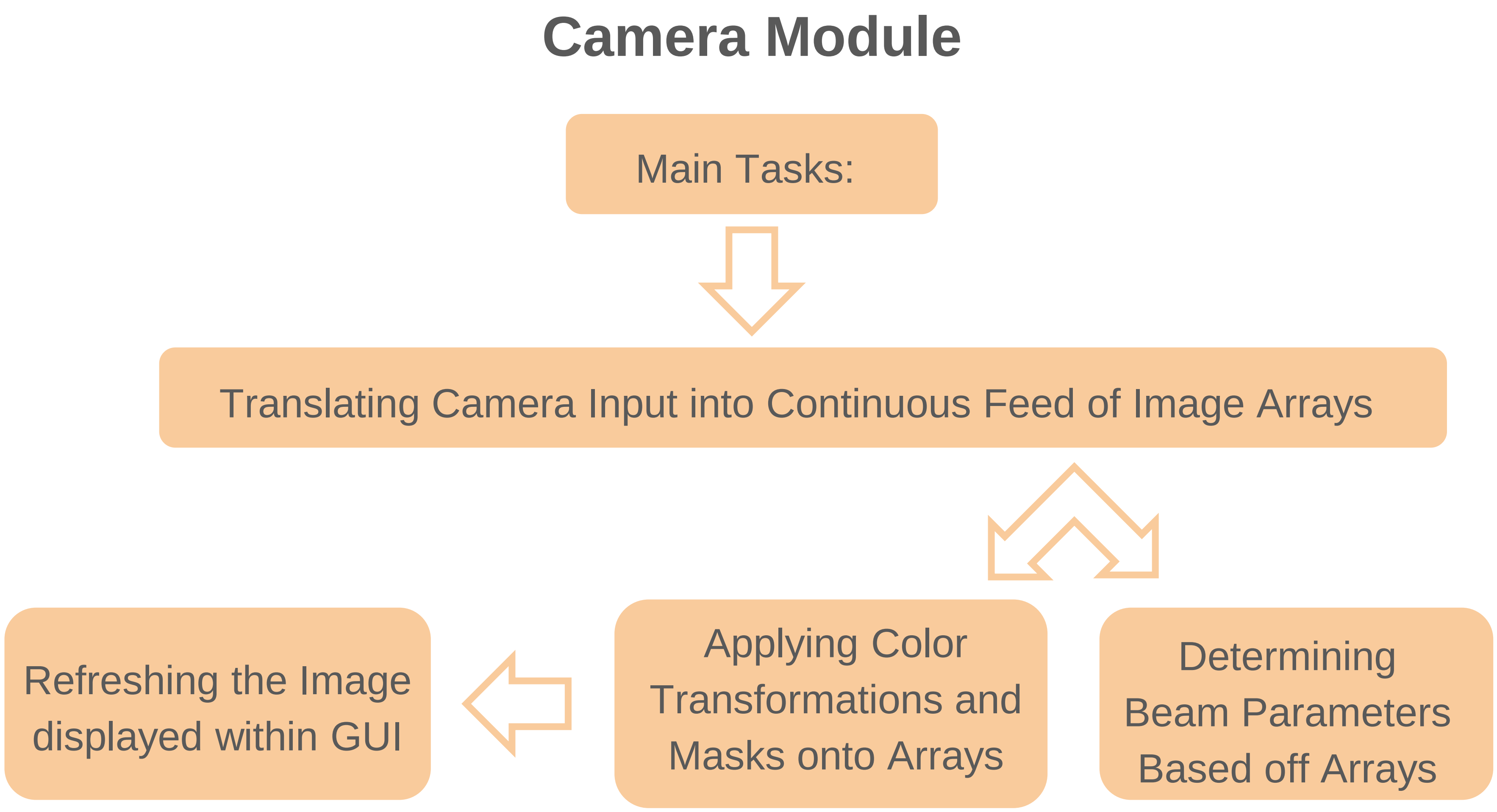

custom_beam_gui.py
Beam_Stats_20220414_195441_.csv

```
Image Width and Height (in pixels)
2600, 1960
X Centroid and Y Centroid Locations (in pixels)
664.3255813953489, 1137.2558139534883
D4σ X and D4σ Y Values (in µm)
46.794092530194874, 166.26720660234565
Angular Divergence in X and Y Orientations (in radians)
0.004679409256434968, 0.016626720813448598
M^2
2.621561906529692
```

Beam Stats .csv



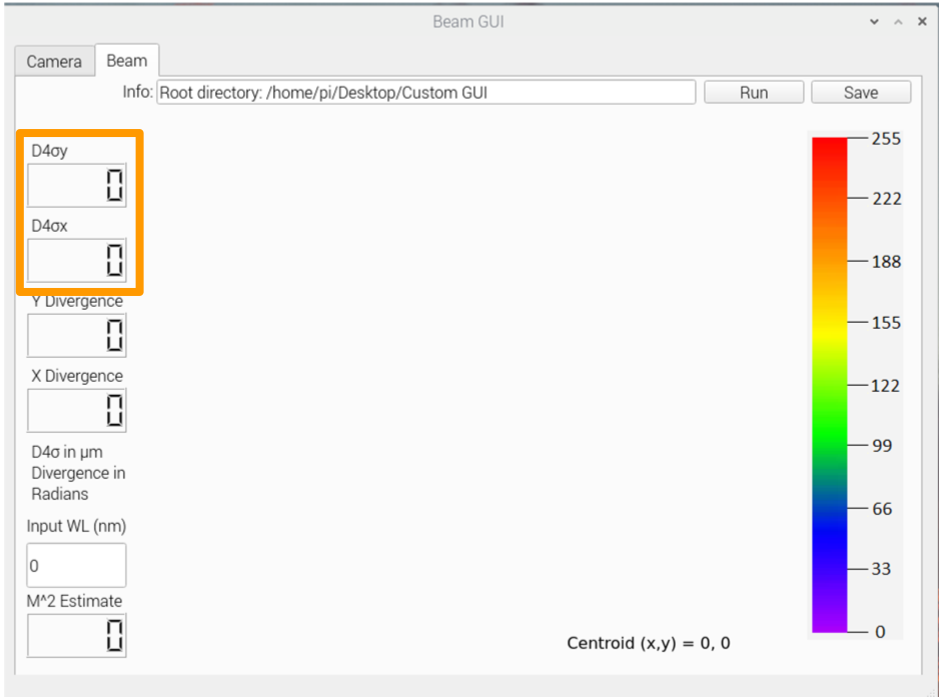
Intensity Profile (X and Y) .pngs


Camera Module
Main Tasks:
Translating Camera Input into Continuous Feed of Image Arrays
Refreshing the Image displayed within GUI
Applying Color Transformations and Masks onto Arrays
Determining Beam Parameters Based off Arrays

Camera Module Features

Image Based Parameters

D4σ beam waists are based off image moments, multiplying by the physical pixel dimensions gives physical waist size



Beam Waist Calculations, Step by Step

Determine Image Moments
(performed via CV operation)

$$M_{ij} = \sum_x \sum_y x^i y^j I(x,y)$$

Find Centroid
(performed by code)

$$\{\bar{x},\ \bar{y}\} = \left\{ \frac{M_{10}}{M_{00}}, \frac{M_{01}}{M_{00}} \right\}$$

Calculate D4σ Beam Radius
(performed by code)

$$D4\sigma = 4\sigma = 4\sqrt{\frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)(x-\bar{x})^2\,dx\,dy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)\,dx\,dy}}$$

Simplified

$$D4\sigma_x = 4\sqrt{\frac{M_{20}}{M_{00}} - \bar{x}^2}.$$

$$D4\sigma_y = 4\sqrt{\frac{M_{02}}{M_{00}} - \bar{y}^2}$$

Camera Module Features

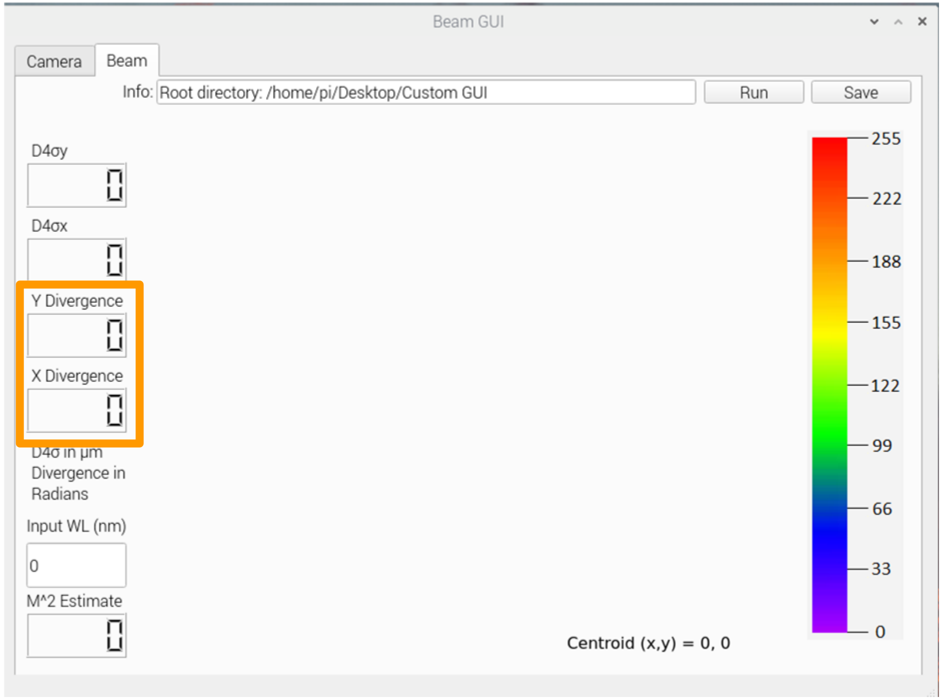
Derived Parameters

Angular divergence determined based off Gaussian approximations with a focusing optic

$$divergence = \tan^{-1}\left(\frac{W_f}{f}\right)$$

W_f = Beam Waist

f = Focal Length of Optic (10cm)



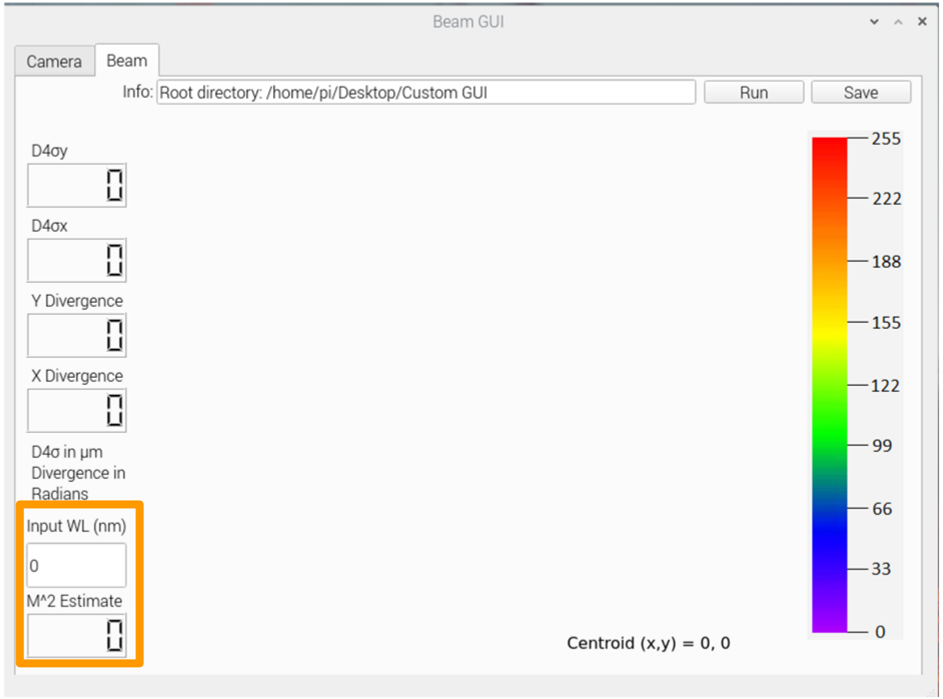
Camera Module Features

Input Based Parameters

M^2 Estimate outputs based off of user input beam wavelength

$$M^2 = (W_f \times \pi \times \theta)/4\lambda$$

W_f = Beam Waist
θ = Angular Divergence
λ = Beam Wavelength



M^2 Comments:

M^2 labelled as ‘M^2 Estimate’ within Profiler GUI:

- ISO/DIS 11146 requires at least 5 measurements of beam waist
- Gaussian Divergence approximation introduces further uncertainty
  - Only valid for Gaussian Beam

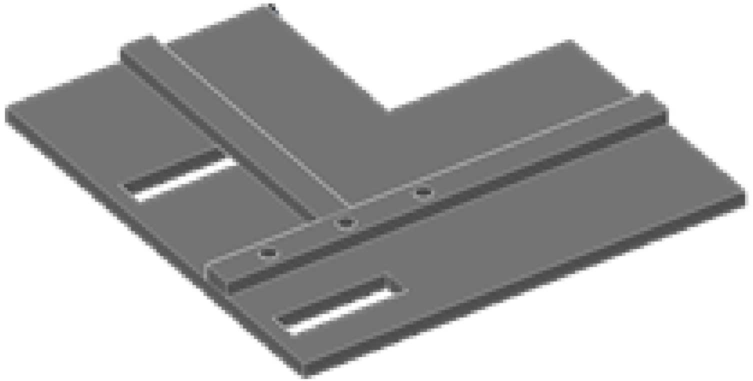
4λ present in denominator because formula normally intakes beam radius and divergence half angle (½ ⨯ ½ = ¼)

III: Freely Attachable

- Design Custom Housings to Interface System with Laser Output Couplers

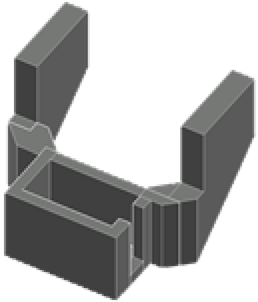
Optical Track

- Provides continuous placement of optical elements
- Holes allow for mating with slotted base and silver post for mounting



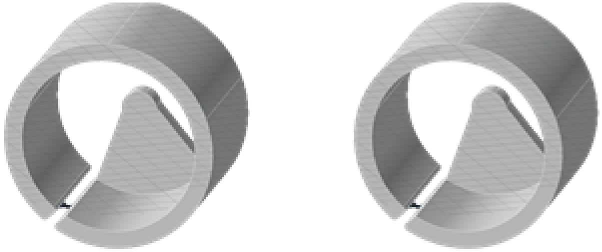
Stand Adjustment Mechanism

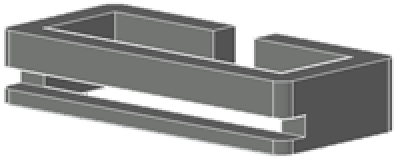
- Stand motor is suspended below the optical track
- Apparatus shown on top allows stand to be rotated at a distance by the stand motor



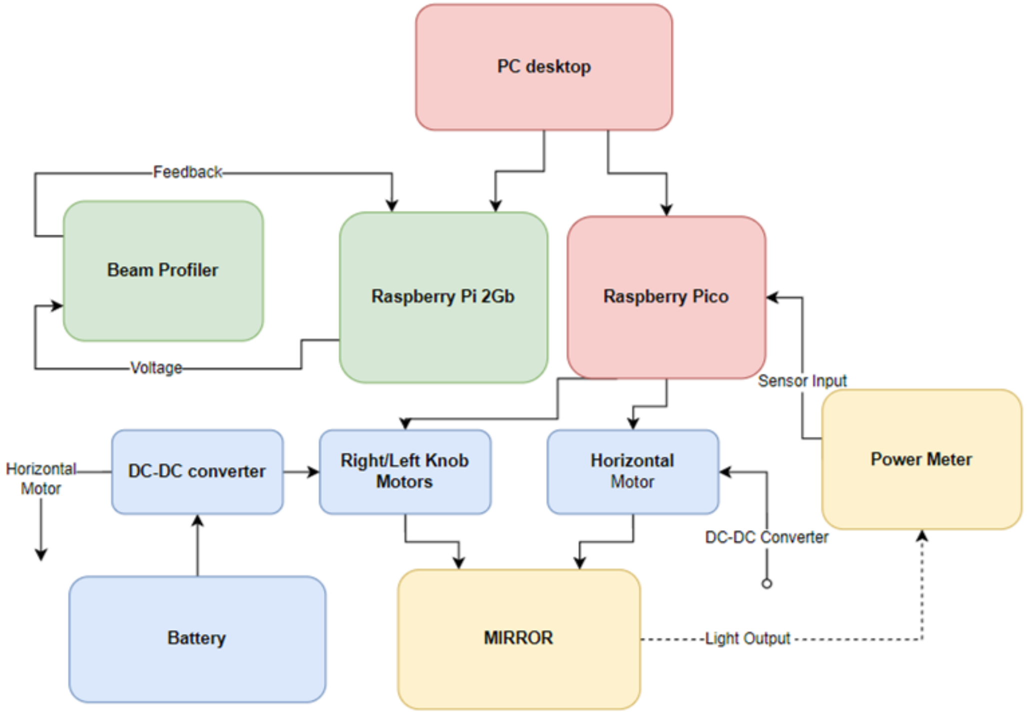
Knob Adjustment Mechanism

- Pieces shown on top are attached to continuous motors
  - Fit over mirror mount knobs to adjust mount
- The continuous motors are held rigid within the casing shown on bottom





Overall Block Diagram



AJ assist: Bryce
Bryce assist: AJ
Nick assist: Matt
Matt assist: Nick

Design Specifications

Design Goals and Levels of Satisfaction

<table>
<tr><th>Specification</th><th>Goal</th><th colspan="2">Satisfaction</th></tr>
<tr><td>Minimum Achievable Output Power</td><td>75% Max</td><td colspan="2">✓✓</td></tr>
<tr><td>Workable Laser Wavelength Range</td><td>400nm - 700nm</td><td colspan="2">✓✓✓</td></tr>
<tr><td>Workable Laser Output Power Range</td><td>0.1mW - 1W</td><td colspan="2">✓✓✓</td></tr>
<tr><td>Maximum Laser Beam Half-Angle Divergence</td><td>17.5mrads</td><td colspan="2">✓✓✓</td></tr>
<tr><td>Workable Laser Beam Diameter</td><td>1mm - 10mm</td><td>✓✓✓</td><td>✓✓</td></tr>
<tr><td>Time to Lase</td><td>< 5 minutes</td><td colspan="2">✓✓✓</td></tr>
</table>

<table>
<tr><th>Specification</th><th>Goal</th><th colspan="2">Satisfaction</th></tr>
<tr><td>Data Refresh Rate</td><td>60 Hz</td><td>✓✓✓</td><td>✓</td></tr>
<tr><td>Setup Time</td><td>< 1 minute</td><td colspan="2">✓✓</td></tr>
<tr><td>Weight limits</td><td>< 6.0 kg</td><td colspan="2">✓✓✓</td></tr>
<tr><td>Dimensions</td><td>Whole System Storable in a Cubic Foot</td><td colspan="2">✓✓✓</td></tr>
<tr><td>Power Consumption</td><td>< 20 W</td><td colspan="2">✓✓✓</td></tr>
<tr><td>Cost</td><td>< $1000</td><td colspan="2">✓✓✓</td></tr>
<tr><td>Spatial Degrees of Freedom</td><td>3</td><td colspan="2">✓✓</td></tr>
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Finances

Project cost By Category

Component Classification	Cost ($)
Electrical	127
Mechanical	31
Optical	205
Replacement costs	105
Total cost	468

- Replacement Parts required included a new RP Camera, Photodiode and FS90R Continuous Servo.

Material	Quantity	Cost ($)
Raspberry Pi 2 Gb	1	62.45
Raspberry Pi Pico	1	8.50
Fs90R Continuous Servo	4	29.90(14.95 for original and replacement)
DS3218 Positional Servo	1	16.36
STDC 4 D-Cell Battery Pack	2	8.90
PCB Boards	5	23.76
UA741CN Op Amp	1	0.45
BPX65 Photodiode	1	12.18
10K Ohm Resistor	1	0.00
LM2596 DC converter	6	10.99
Raspberry Pi Camera	2	150.00 (Original 60 Replacement 90)

System Issues

- Low Frame Rate on Beam Profiler
- Ghost Readings on Photodiode
  - Plasma from Laser
  - Voltage Converter
- Machine Learning Failure

Conclusion

- Achieved All Major Goals
  - Failure to Reach Advance Goals Outlined in 120 Page Paper such as: Fiber Coupling, Automatic Wavelength Adjustment, Mode Modulation
- Most Important Specifications Met or Exceeded
  - Under Budget, <5 Minute Lasing Time, Max Power Adjustment
- Further Developments…
  - Create Housing to ‘Clean Up’ PCB and Profiler Computer
  - Allow Linear Translation of Profiler for True M^2 Value
  - Optimize Software to Increase Lasing Speed and Profiler Frame Rate