LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Note	**LIGO-T2100205–v1**	2021/05/24

LIGO Laser Beam Tracking

SURF Student: Anirban Bairagi
Mentors: Yehonathan Drori, Tega Edo, Rana Adhikari

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW22-295
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

http://www.ligo.caltech.edu/

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1 Introduction

Gravitational Waves are produced by the bulk accelerated motion of matters, that propagates as waves in the fabric of spacetime at the speed of light. The existence of Gravitational Waves were first predicted by Albert Einstein in 1916 as a consequence of his work on General Relativity. The LIGO interferometers were built using the basic idea of Michelson interferometer and its precise strain measurements rely on the laser beam resonators in the optical cavity of the interferometers. Many years of relentless efforts and several technical upgradations in the detectors made by the scientists helped aLIGO to achieve the sensitivity to detect more than 50 GW events till date.

When the GW passes through the interferometer its arm length increases and decreases consecutively which causes change in differential arm length during the event. The intensity of the recombined light at the detector readout which is a function of the differential arm length (DARM) of the interferometer, gives the infinitesimal gravitational wave strain as shown in Figure 1. The LIGO detector is highly susceptible to various kind of noises which are basically unwanted signal produced by interactions among detector subsystems or with the surrounding environment that gets added to the GW strain data. Here, we are interested in the Fabry-Perot cavity and test masses of the detector. In this project we are trying to detect the position of the laser beam spot on the test masses. The aLIGO is not free from scattered light noise. The scattering of light helps us to see the scattered beam spot from any angle on the mirror surfaces. Due to irregularities and point scatterers of the mirror, the light undergoes deflection from its path defined by specular reflection and hence scattering occurs. The angular motion of the mirrors causes oscillatory translational motion of the beam spot on the mirror. Thus, tracking the position of the beam has become one of the important task within LIGO community.

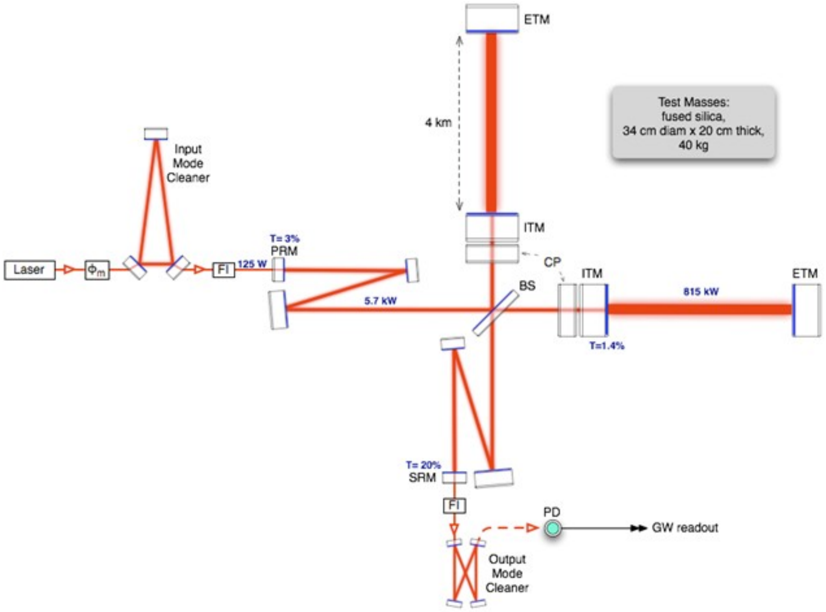

Figure 1: Schemetic Diagram of LIGO detector

One should not observe the beam spot ideally when it is viewed at an angle to the beam axis since no light deflects according to the laws of specular reflection. However, due to scattering of light the beam spot can be observed from different angles with varying intensities according to the Bidirectional Reflection Distribution function (BRDF) of the mirror.

$$\mathrm{BRDF} = \frac{\mathrm{P}_s/\Omega}{\mathrm{P}_i \cos\theta_s}$$

where P_i and P_s are incident and scattered power and θ_s is the scattering angle and Ω is the solid angle subtend at the CCD camera used for capturing the image of the test mass. We are mostly interested in large angle scattering where the optic behaves as a Lambertian surface. Here Basler ace acA640-120gm camera equipped with a Gigabyte Ethernet (GigE) interface has been installed for faster data transmission over ethernet network as shown in Figure 2. Two lens telescope system is placed between GigE camera and mirror to focus the beam spot onto the GigE camera sensor while ensuring lenses and camera are placed perpendicular to scattered beam axis and optimum utilization of the CCD pixel arrays. It gives the videos of the scattered light coming from the surface of the test masses.

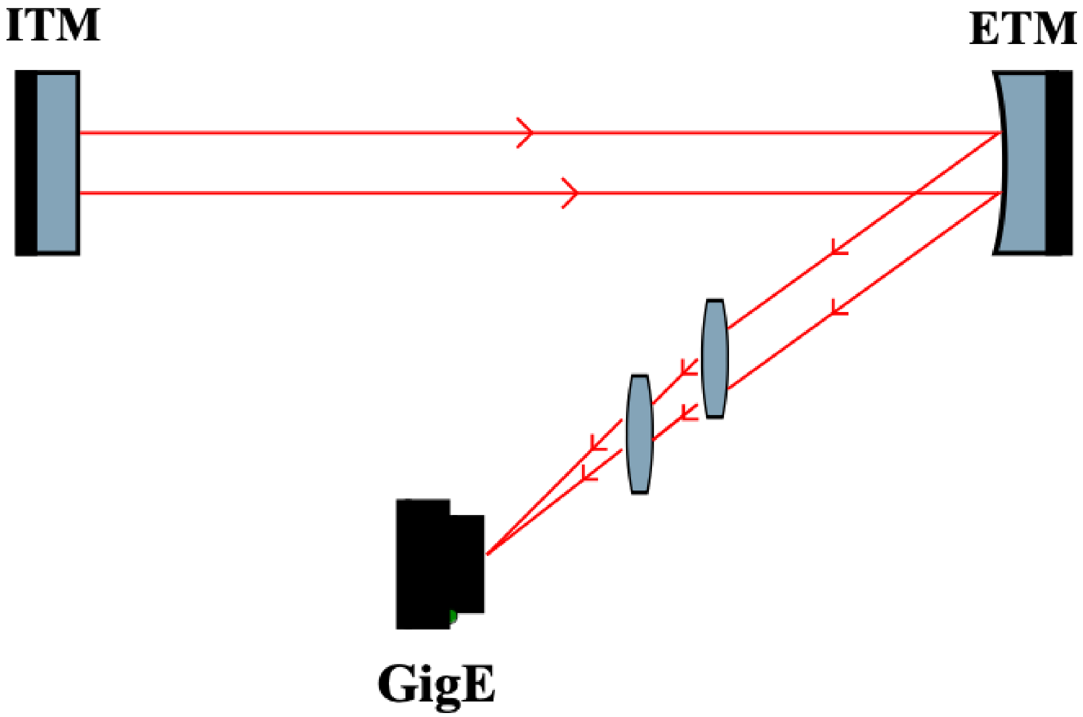

Figure 2: GigE camera setup for imaging the scattered light

Pooja Sekhar, Milind Vaddiraju have already tried some classical image processing techniques which failed to detect the centroid of the beam because the beam do not retain its gaussianity after scattering due to irregularities of the mirror surface. In Figure 3[2], on plotting the intensity vs pixel number along a particular axis of the image of the beam spot, the intensity profile deviates quite a bit from the expected Gaussian profile. This is caused due to the scattering from point defects.

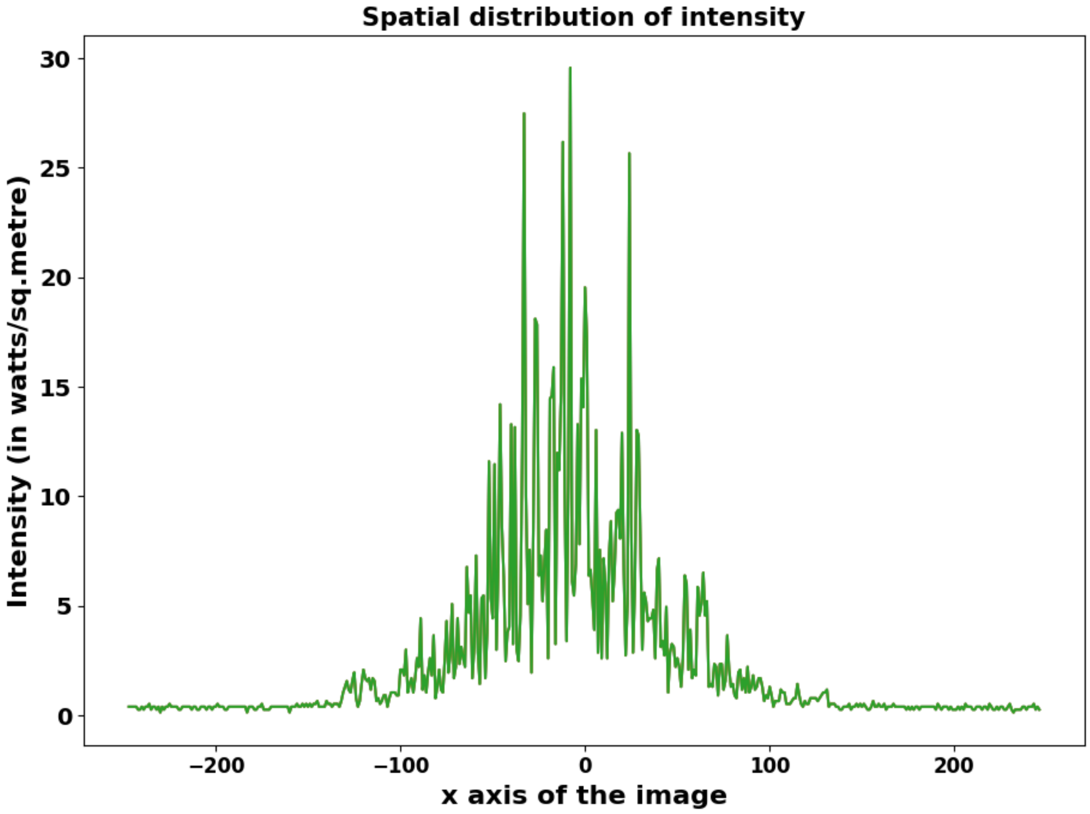

Figure 3: Deviation from Gaussian intensity profile

Several attempts made by them using Neural Networks has shown reasonable good results in comparison to the classical methods. Neural networks were trained with hyperparameters tuned using a grid search and beam spot motion at 0.2 Hz with an amplitude of about 3mm is tracked with maximum error under 20% [1]. But we require better accuracy for our purpose.

2 Motivation

These are future goals of GW researchers for which our current work on laser beam tracking is very crucial. We need to detect the position of the beam spot to understand the angular movement of the mirror so that feedback control system attached to the test masses fix its position as shown in Figure 4. Also the position at different instances give the velocity of the beam spot and the RMS velocity can be used to reduce some noises from the data and will help us to characterize the detector.

3 Objective

Our main objective is to get the position of the beam spot at every instances with better accuracy using some traditional image processing techniques along with some Deep Learning models. Although we will be stick to detecting the position only in this work, but in future it will help in reducing some noise from the data and analysing the motion in a better way if we become successful.

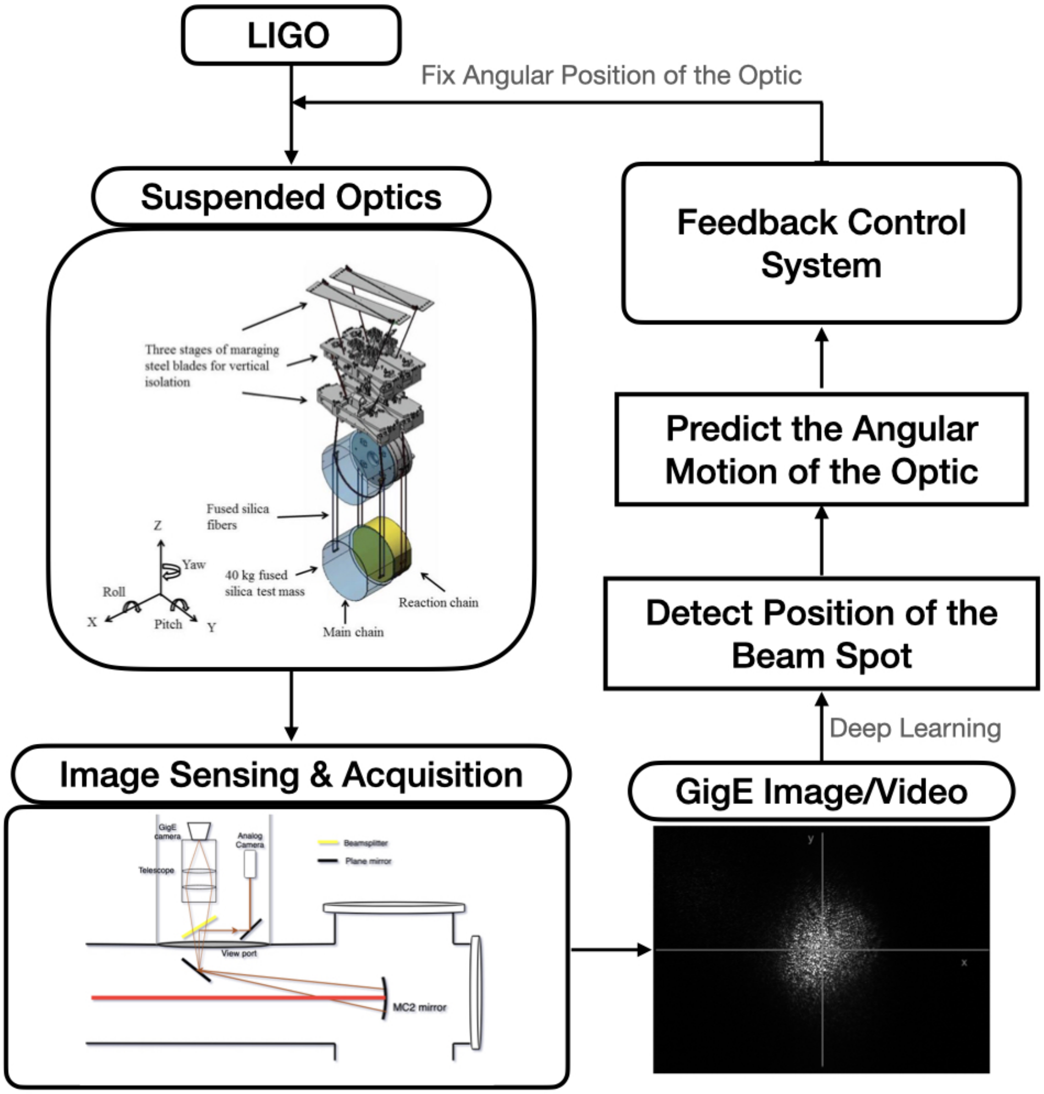

Figure 4: Angular Control of Suspended Optics

- Apply some traditional image processing techniques including marching pixels[4] and binarizing the image for a suitably chosen threshold followed by calculating the moment of the image[3] to see how well these classical approaches work in detecting the centroid.

- Generate simulated video of beam spot motion. Since Deep Learning models are expected to produce better results and we lack labelled image datasets for training, we need to simulate scattering light images comparable to the GigE images.
- Develop a Convolutional Neural Network (CNN) model to extract features from the images i.e. finding the centroid of the beam and angular deflection of the mirror.
- Develop a Long Short Term Memory (LSTM) model to predict the position based on the previous positions of the beam spot.
- Test the efficiency of the models by applying it on real labelled image datasets obtained from the GigE camera by changing the beam spot position precisely.

4 Work Plan

4.1 Week 1-2:

At first I will apply some traditional image processing techniques to detect centroid from the GigE images. One of the method is to binarize the pixel values of the image and then obtain the centroid from moment of the image which is basically weighted image pixel intensities[3]. I am also planning to use marching pixels algorithm to find out the centroid[4].

4.2 Week 3-4:

We will simulate some scattered light images. Assuming the laser beam to be perfectly gaussian we will take some roughness and point scatterers on mirror surface into consideration to generate the beam spot images corresponding to their centroid position.

4.3 Week 5-7:

These generated images along with their positions will be used to train some CNN models like YOLO or Faster-CNN. Once these models are trained properly we will be using it on our actual dataset obtained from the GigE camera.

4.4 Week 8-10:

We are planning to use some RNN models like LSTM which can be used to analyze the behaviour of the motion from a timeseries data of the position of the beam spot. It can be later used along with the CNN to predict the position of the beam if its previous positions are known very accurately.

5 Simulation of Beam Spot

Here we will consider a fundamental laser beam with a linearly polarized, Gaussian field distribution in the beam waist

$$\vec{\mathbf{E}}(x', y', 0) = \vec{\mathbf{E}}_0 e^{-\frac{(x'-\mu_x)^2+(y'-\mu_y)^2}{w_0^2}} \tag{1}$$

where E_0 is constant field vector in the transverse (x,y) plane and (μ_x, μ_y) is the position of the centroid of the beam on the plane.

$$\tilde{\mathbf{E}}(k_x, k_y, 0) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \vec{\mathbf{E}}(x', y', 0) e^{-i(k_x x' + k_y y')} dx' dy' \tag{2}$$

$$\tilde{\mathbf{E}}(k_x, k_y, z) = \tilde{\mathbf{E}}(k_x, k_y, 0) e^{ik_z z} \tag{3}$$

Then, the field at the object plane becomes

$$\vec{\mathbf{E}}(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{\mathbf{E}}(k_x, k_y, z) dk_x dk_y \tag{4}$$

Using these equation we can construct beam spot centred at (μ_x, μ_y) at any irregular mirror surface by varying the z over the surface. Now the difference between the field for varying z and field for constant z gives the field of scattered light.

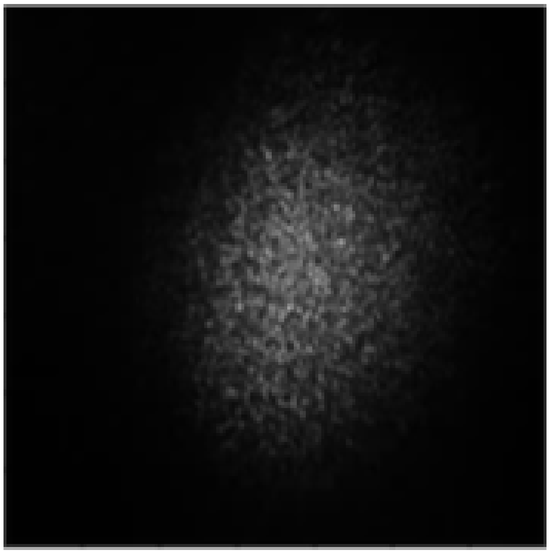

Figure 5: Generated Scattered Beam Spot

Suppose, the mirror surface is at an approximate distance z from the source plane. Then, the electric field of the scattered will be

$$\vec{\mathbf{E}}_{\text{scatter}}(x, y, z) = \vec{\mathbf{E}}(x, y, z) e^{ik_z \Delta z} - \vec{\mathbf{E}}(x, y, z) \tag{5}$$

where $\Delta z(x, y)$ is the height of irregularities on the mirror surface. For the places of no irregularities on the mirror $\Delta z = 0$.

Thus, the intensity of the scattered light is

$$\mathrm{I}_{\text{scatter}}(x, y, z) = \vec{\mathbf{E}}^{\star}_{\text{scatter}} \vec{\mathbf{E}}_{\text{scatter}} \tag{6}$$

Using these formulation we can simulate beam spot as shown above in Figure 5.

References

[1] Milind Kumar Vaddiraju, Mentors: Rana Adhikari, Gautam Venugopalan, Koji Arai, *Laser beam position tracking for LIGO interferometers*. LIGO-SURF Report (2019).

[2] Kruthi Krishna, Mentors: Gautam Venugopalan, Koji Arai, Rana Adhikari, *High FidelityProbe of Optical Scatter from Point Defects*. LIGO-SURF Report (2019).

[3] `https://learnopencv.com/find-center-of-blob-centroid-using-opencv-cpp-python/`

[4] `https://ieeexplore.ieee.org/document/5479520`

[5] `http://blue.ligo-wa.caltech.edu:8000/40m/40mHomePage`