LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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2023 LIGO SURF Project: Interim Report #2

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1 Introduction

1.1 Background

The Laser Interferometer Gravitational-wave Observatory (LIGO) consists of two gravitational wave detectors operating in unison at Hanford, Washington and Livingston, Louisiana in USA. Extremely precise laser interferometry is used in these facilities to measure tiny distortions in space-time caused by the passage of gravitational waves. They are part of a collaborative effort by scientists around the world, that include gravitational wave detectors KAGRA (Japan), VIRGO (Italy) and the upcoming IndIGO(India).

The detectors consist of Michelson interferometers built over two L-shaped arms, each 4km in length. Laser light is split and sent down both arms to bounce off the end mirrors and travel back to the starting point, where they recombine to form an interference pattern. When gravitational waves pass through the interferometer, they cause a variation in arm lengths of the interferometers which is reflected in the interference pattern. The long length of the interferometers arms provide for the high sensitivity required to sense the effects of gravitational waves, which are very faint. The interferometer arm cavities are a key component of LIGO, and the precise control of cavity parameters is essential for accurate detection of gravitational waves [1].

The 40m prototype of LIGO at Caltech is a 1:100 scale model of the LIGO facility. It serves as a testbed for prototyping new technologies for future upgrades to the Advanced LIGO (aLIGO) detectors, as well as to carry out minor side experiments.

1.2 Motivation

The 40m facility uses an Arm Length Stabilization (ALS) system, to lock the main laser frequency to the interferometer degrees of freedom through various feedback loops. A frequency doubled auxiliary laser (AUX) is injected into the arms of the interferometer, and locked to the arm cavity using Pound-Drever-Hall (PDH) technique [2][Fig.1]. The AUX laser is summed with the main laser on a photodiode, to produce a beat note that is indicative of the relative fluctuations between main laser frequency and arm cavities. The beat note is used as an error signal to drive the feedback of the Arm Length Stabilization (ALS) system, that keeps the interferometer cavity resonant with the main laser frequency [3].

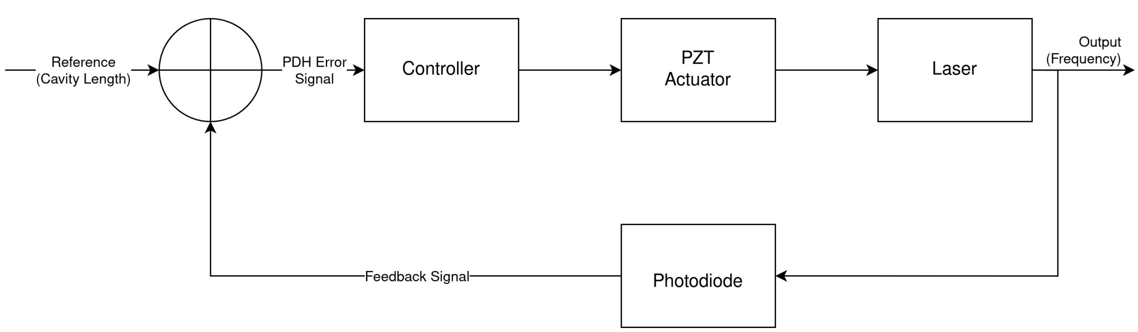

Figure 1: Flowchart showing the Pound-Drever-Hall setup

The AUX NPRO laser is fitted with a piezoelectric (PZT) modulator to enable analogue frequency control through phase modulation. Currently, the limitations of the current analogue PDH controller and mechanical resonances of the laser's PZT actuator diminish the controller's performance at lower frequencies, and brings down the bandwidth($\sim$10kHz). A digital implementation of the servo controller (controller shown in Fig. 2) to compensate for the PZT's resonances could increase bandwidth, and provide a robust framework to implement faster and more optimal controller designs [3].

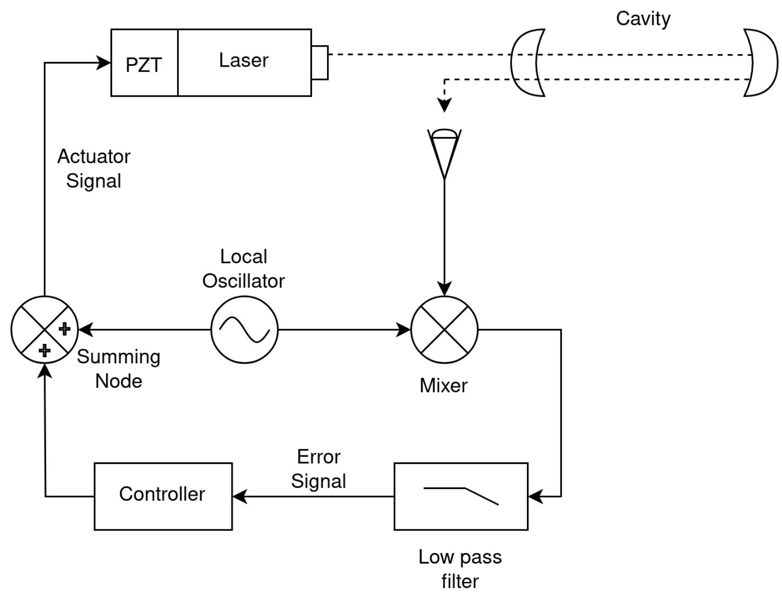

Figure 2: Schematic of the AUX laser locking setup

As the AUX laser is being used as a reference for the main laser, stability of the AUX laser is crucial for stability of the main laser. Specifically, the area of interest is in the 10Hz - 20kHz range, where the contribution of the AUX laser to the beat note fluctuation is present. The new digital controller would focus on suppressing noise at this frequency range, as well as overall improvement in bandwidth over the current PDH loop. The controller should also be able to detect if the system is out of lock, and switch to a filter designed for fast lock acquisition then switch back to the stable lock filter.

The improvements in the controller design could lead to implementation of better calibration techniques like Simultaneous Oscillator Calibration (SoCal), leading to better accuracy in measurements. In an astrophysical context, it would enable better triangulation of events in the sky and better estimation of luminosity distance. Improved laser stability could also facilitate profiling and surface roughness characterization of the test mass (mirror) surface. The end goal is to not let the uncertainty in detector response caused by noise and calibration errors limit future measurements.

This interim report consolidates the work done as part of the LIGO SURF program over the span of seven weeks.

2 Abstract

The LIGO interferometers need to robustly lock its various degrees of freedom to be sensitive to Gravitational Waves. The LIGO 40m prototype uses an auxiliary (AUX) laser as a reference to lock the main laser to the arm cavity and stabilize it. The AUX laser is stabilized by locking it to the arm cavity using the Pound-Drever-Hall (PDH) technique. The stability of the AUX laser is crucial for the stability of the main laser. Mechanical resonances of the AUX laser's piezoelectric (PZT) actuator and the rigid nature of the currently implemented analogue PDH controller limits the performance of the system, hindering noise suppression especially at low frequencies. This project aims to develop a digital controller to replace the currently implemented AUX laser locking system. A digital controller will be more robust and easily customizable. Specifically, the features to be implemented include better controller performance in the 10Hz-20kHz range, where the AUX laser noise has greater contribution, supplying an increase in bandwidth over the current analogue system, enable fast lock reacquisition when lock is broken and adding resonant gain filters at specific resonant bands to facilitate calibration of the interferometer.

3 Learning control systems theory

I learned a lot more about controls theory over the duration of the program, specifically I got more familiar with fitting bode plots, stability margins, controller design, pole placements and LQR theory. The goal is to get the proper foundations of basic controls theory down and then check out some nonlinear control theory which could be useful while designing the controller. I played around with the Moku:Go a bit more, figured out how to interface it with Moku's Python API and take readings, and control the hardware over Python.

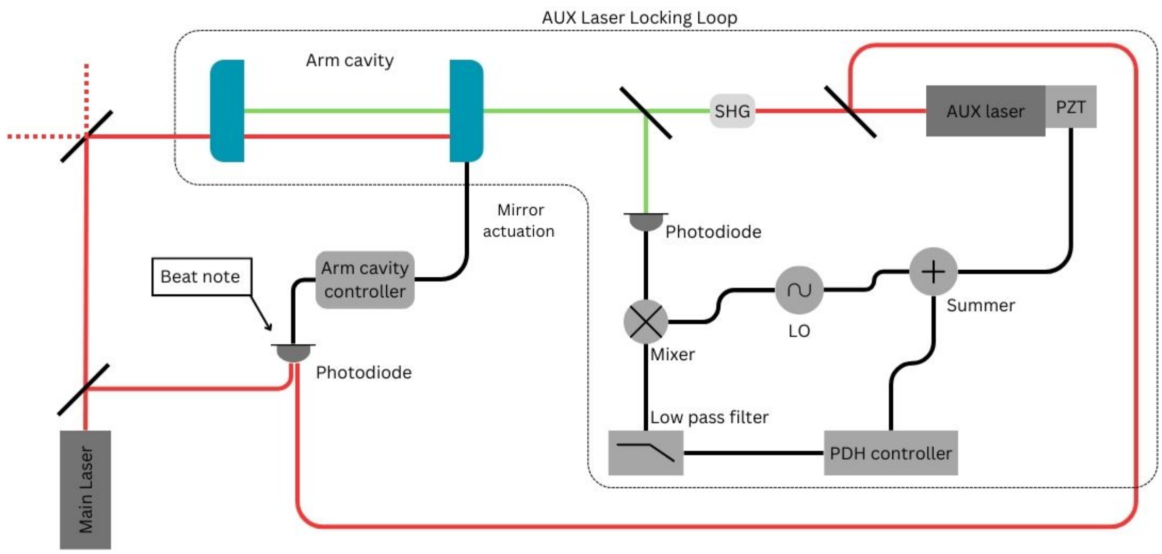

Figure 3: Simplified diagram showing how the AUX locking setup feeds into the main laser system

The references used were mainly, Feedback Systems by Astrom and Murray [6], Schaum's Feedback and Control Systems [7], Gautham Venugopalan's thesis [3], LIGO notes on PDH technique [2], lectures on the topics on YouTube and other resources.

4 Measuring the AUX-PDH open loop transfer function

The open loop transfer function (OLTF) of the XAUX-PDH loop was measured using the Moku:Go, using its frequency response analyzer instrument. The excitation was summed with the error signal sent to the PDH controller and the responses were measured at the error signal point before and after summation into the loop. The Moku:Go provided a swept sine excitation and the summing into the loop was done using SR560 preamplifier. A Python script was used to read the exported data, plot and find its stability margins and bandwidth. Further readings should include multiple readings, to try and get an averaged data, as well as to measure the transfer functions of the individual components of the system to compare with the model that is being built.

Currently, control is done by the universal PDH (uPDH) Servo box, that includes both the controller and a demodulator to demodulate the modulated green laser signal. The controller

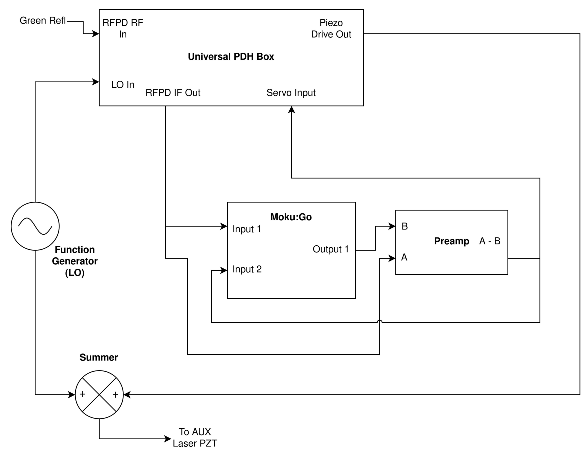

Figure 4: Wiring diagram of the ALS setup at the 40m

part is the first thing that is to be replaced with the Moku:Go. Ultimately, the whole system, consisting of the uPDH box and the function generator (local oscillator) is planned to be replaced with the Moku:Go.

Figure 5: The AUX laser locking setup at the 40m lab

5 Optimal Controller

The goal of the project is to develop and optimize a controller that can lock the laser to the cavity. Optimising a controller involves defining a cost function and then tweaking controller parameters to minimse the cost function. A PID controller can be used as a base controller, and then various methods of optimization, like adding a lead compensator, LQR tuning, or particle swarm optimization can be tested to see which gives a better controller.

An added step is to make the controller in two stages, switch to a controller with a faster response time when lock is broken, to aggressively bring the lock back, and switch to a different controller that can hold the lock more stable once acquired. Linear controllers consider only a linear estimation of the system, and some finer information is lost in this approximation. A potential next step would be to investigate nonlinear controllers and use nonlinear controller design principles to design an even more robust controller.

6 Code

A script was written (plotter.py) to read the exported frequency response data file from the Moku:Go, draw the bode plots as well as calculate the stability margins. This will make reading transfer function measurements made in the future easier.

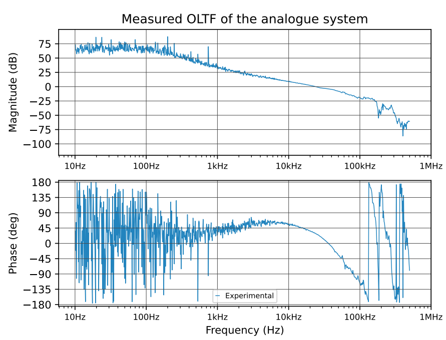

Figure 6: Bode plot of OLTF of the plant measured using the Moku:Go

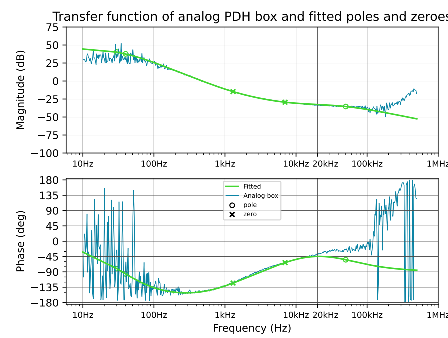

Figure 7: Measured transfer of the PDH box, and fitted frequency response

The main code can now simulate the modelled components and plot its transfer function and stability margins, along with the data collected from the Moku:Go. The stability of the system can now be checked with its impulse response. The poles and zeros of the analog PDH box were fitted by eye. The fitted model has a similar frequency response to that of what was measured using the Moku:Go. The low pass filter is taken as 2^{nd} order Butterworth, instead of 2^{th} order as was given in Gautam's thesis.

Now that the basic framework is ready, new controller designs can be simulated with the code and open loop and closed loop response, stability margins and impulse responses studies.

The code designed by Radhika and Anchal, which can implement a filter in the Moku:Go given zpk values will be instrumental in testing out the controller designs.

7 What's next

Now that the basic goals and framework to design the controller are laid out, testing of new controller designs can start. Unfortunately, due to the 40m interferometer upgrades, the plant was down for long periods of time and actual work on the AUX laser loop was not possible.

The current plan is to build a tabletop version of the loop, simulating the arm cavity with as SR560 preamplifier and running the controller tests. The first step is to design a controller that can improve noise suppression in the 10Hz-2kHz range, and develop a filter switching

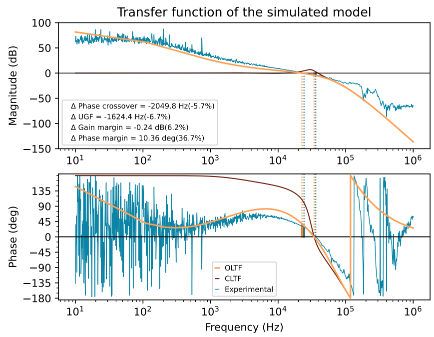

Figure 8: Measured and simulated transfer of the plant, with stability margins

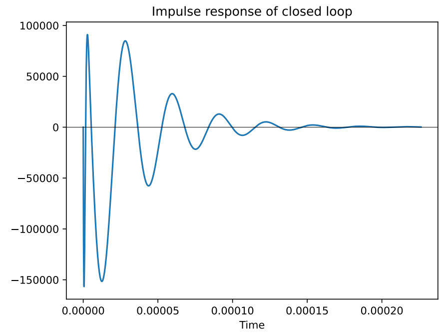

Figure 9: Impulse response of the plant

system for fast lock acquisition and maintaining stable lock once acquired. This will be the goal of the project in the final weeks.

References

[1] https://www.ligo.caltech.edu/page/ligos-ifo

[2] *Notes on the Pound-Drever-Hall technique*, LIGO Technical Note (1998), https://dcc.ligo.org/public/0028/T980045/000/T980045-00.pdf

[3] Gautam Venugopalan, *Prototype Interferometry in the Era of Gravitational Wave Astronomy*, Chap II (2022), https://thesis.library.caltech.edu/14288/3/main.pdf

[4] Craig Cahillane, *Calibration Methods for Current and Future Gravitational Wave Detectors*, MIT General Relativity Informal Tea Time Series Talk (2019)

[5] The plans for the project is based on discussions with Professor Rana Adhikari *(Experimental Gravitational Physics, LIGO Lab Caltech)* and Radhika Bhatt *(Graduate Student, Adhikari Research Group).*

[6] Karl Johan Astrom, Richard M. Murray, *Feedback Systems*

[7] *Schaum's Outline of Feedback and Control Systems*