LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note **LIGO-T22xxxxx–** 2022/05/13

2022 LIGO SURF Project Proposal: Emissivity Engineering for Radiative CryoCooling

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1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) measures gravitational waves and is one of the pioneering instruments which help detect black holes and neutron star mergers. The instrument, or more accurately, the suspended mirrors used, is highly susceptible to vibration noise. The third-generation upgrade, LIGO Voyager, is planned to improve the sensitivity by an additional factor of two and halve the low-frequency cutoff to 10 Hz by reducing quantum radiation pressure and shot noise, mirror thermal noise, mirror suspension thermal noise, and Newtonian gravity noise.

While the seismic isolator module nullifies the ground vibrations (Newtonian gravity noise), there is still noise due to the thermal vibrations of the system (thermal noise). We nullify these thermal vibrations by installing a cryogenic cooling facility which radiatively cools the silicon test masses to 123.7 K. This project will culminate in the cryogenic Voyager upgrade, starting with the Mariner (Voyager prototype) upgrade at the Caltech 40m Lab.

We first model our cool-down curves in a chamber called the cryostat to then later apply our insights to Mariner. The cryostat system has much noise due to heat leaks. Thus, it becomes necessary to model this noise in our system by estimating unknown parameters like the area of effective heat leak, geometric view factor, and emissivity of the coating used. We do this by obtaining data on the system's response and maximizing the Fisher information about our system's parameters such that the system becomes robust to noise. In other words, we find the optimal control input, which minimizes the covariance matrix to be more certain about our estimated system parameters.

This is done by first finding an estimate of the plant model with the least uncertainty (using Markov Chain Monte Carlo instead of traditional curve fitting) and then finding the optimal control input using the estimated plant model. We repeat the procedure to ensure that the covariance is lower in the optimal input case than in the uniform input case (which will be the initial input used in the MCMC analysis). This optimal control input and experimental configuration can be used for emissivity tests of many other key coating materials for the LIGO Voyager upgrade.

In order to achieve the desired low temperature of 123.7 K and improve the cool-down time, we use these estimated system parameters to control the system such that we can conduct a number of experiments in a short amount of time. We can employ standard linear control techniques to achieve a constant desired temperature of 123.7 K. As the system is non-linear, we may also use non-linear control methods like neural networks to obtain better results.

2 Objective

- Develop a thermal model of the cryostat using radiative heat transfer equations and understand the relation between various system parameters and heat leaks.
- Use Fisher matrix method to find the optimal excitation which gives least uncertainty in the emissivity and other system parameters for a particular experimental configuration. Repeat procedure for different configurations till uncertainty is minimized.

- Assist in the hands-on cryostat experiments to obtain cool-down curves and get the emissivity of the material as a function of time for the optimal experimental configuration and control input.
- Perform linear feedback control on the system for it to reach the desired temperature of 123.7 K. If time permits, perform non-linear control using neural networks.

3 Approach

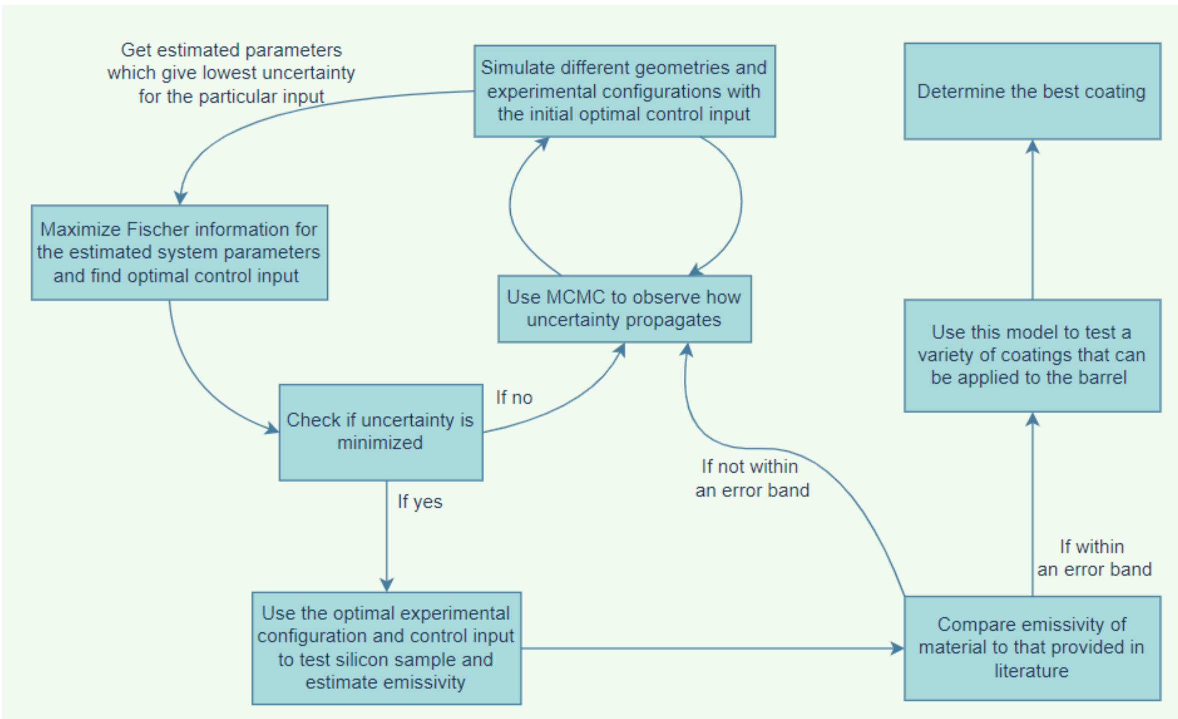

Figure 1: An iterative approach will be used to find the optimal control input and experimental configuration which minimizes uncertainty of the estimated material emissivity

3.1 Obtain Analytical Model of the System

An optimal experimental configuration, found using MCMC analysis (by another SURF student), will give the least uncertainty on the emissivity of the sample and other system parameters for a particular control input. Using this experimental configuration we perform measurements and obtain parameter values which can then be fed in our analytical model of the system.

3.2 Finding the Optimal Excitation Using Fisher Matrix Method

For a particular estimated system model, we maximimize the Fisher matrix of the system, which directly translates to minimizing the covariance matrix. This technique allows us to redistribute input excitation to obtain the optimal control input such that information received of the system parameters is maximised. This cycle of finding the optimal experimental configuration and optimal input is repeated till uncertainty in the parameters is minimized.

3.3 Estimate the Emissivity of Material as a Function of Temperature

We use the optimal control input and experimental configuration to estimate the emissivity of our silicon sample and compare it with literature. We can also use this same model and input to test and determine the best coating from a wide range of materials.

3.4 Perform Linear Control on the System

With an estimate of the model and system parameters, we can now effectively control the system. We find a control input, using a linear feedback loop, to meet the objective of decreasing the time taken to achieve 123.7 K.

4 Timeline

- **Week 1-2:**

  Study concepts of System Identification theory and Fisher Information Matrix. Also, understand the relation between various parameters and obtain the analytical thermal model of the cryostat system.

- **Week 3:**

  Understand the implementation and derivation of the Fisher Matrix for a simpler model of the cryostat (or some other simple example). Also, optimize the matrix and estimate system parameters for the resultant optimal excitation.

- **Week 4-6:**

  Use pre-acquired system parameters to find optimal excitation for the actual cryostat model. Find the new estimate of system parameters and material emissivity.

- **Week 7:**

  Run iterations, debug code and finalise the results of system identification.

- **Week 8-9:**

  Study linear feedback control techniques. Implement these on the identified system.

- **Week 10-11:**

  Test and debug the code so that the result obtained is satisfactory. Work on the end term paper and presentation of the results obtained thus far.

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