Control in Gravitational Wave detectors

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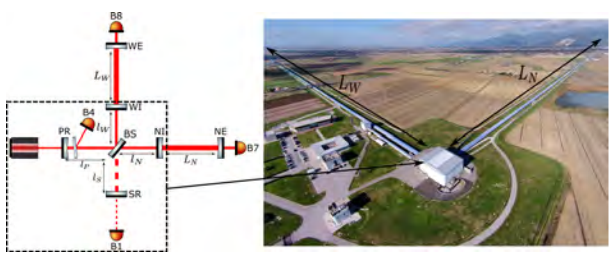
Mathyn van Dael[1,2], Gert Witvoet[1,3], Bas Swinkels[2] and Tom Oomen[1,4]

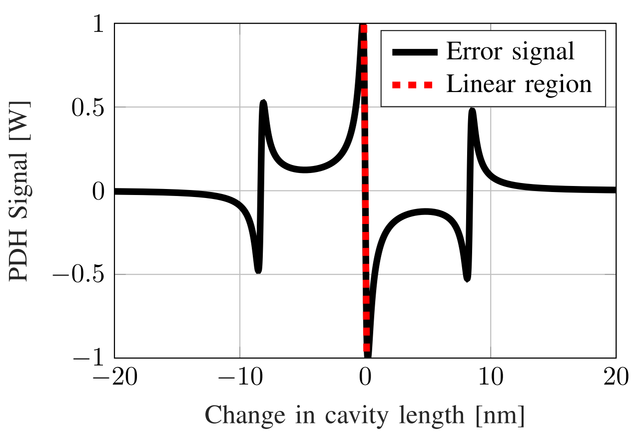
I. Research Overview

Gravitational Wave (GW) detectors measure spatial fluctuations induced by violent cosmic events such as for example the merger of black holes. Current generation detectors such as Virgo [1] and KAGRA [2] employ laser interferometry using several kilometer long arms (L_W, L_N) to measure spatial fluctuations in the order of 1×10^{-18} m. Control systems play a vital role in the operation and sensitivity of the detector.



Cavity locking

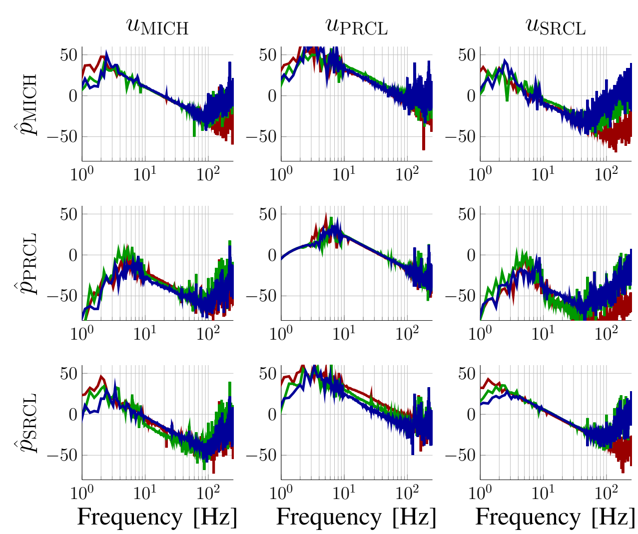
The lengths of optical cavities, i.e. distances between mirrors, have to be actively controlled for the detector to operate. The error signals for these feedback loops use the Pound-Drever-Hall (PDH) [3] method to obtain an error signal (▬) that is locally linear (- - -). The linear region of these error signals are smaller than 1 nm, while the seismically induced motion of the mirrors before the cavities are controlled are in the order of 1 µm.



Currently the cavities are locked by waiting for the error signal to be in the linear regime, at which time the linear feedback controller is engaged. Three cavities furthermore have to be locked simultaneously, requiring all three cavities to be in the linear regime of their error signal. The combination of the many degrees of freedom and poor weather conditions complicates the locking procedure and results in a reduced duty cycle of the detector. The goal of this research is to estimate the cavity lengths in a wider range of the non-linear error signal using non-linear state estimation techniques, to allow faster locking of the cavities and increase the duty cycle of the detector.

System with time-varying levels of interaction.

Three degrees of freedom in the Virgo detector exhibit strong levels of interaction and these interaction terms furthermore vary in amplitude and direction in a timespan of minutes [4]. The figure below shows the MIMO frequency response of the plant for the three loops, where the colored lines represents measurements of the frequency response, each taken one week apart. The SISO control loops require sufficient stability margins to guarantee MIMO closed-loop stability. These degrees of freedom also couple strongly to the sensitivity of the detector and low bandwidth controllers with large roll-off is therefore desired to minimize this coupling. The required stability margins therefore pose a limit on the amount of roll-off that can be achieved. The goal of this research is to develop a method maximizes the system performance in view of the varying levels of interaction.



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II. Seminar Topic - *Integrated Dynamic Error Budgetting and $\mathcal{H}_2$ synthesis*

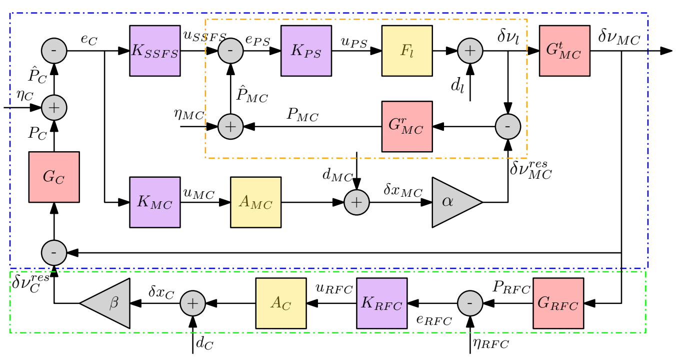
This section discusses the development of an integrated Dynamic Error Budget (DEB) and $\mathcal{H}_2$ synthesis.

A. Problem formulation

The arms that determine the interference pattern of the detector constist of cavities in which the light resonates up and down several hundred times in order to increase the effective length of the cavity. This resonance condition is attained when it holds that

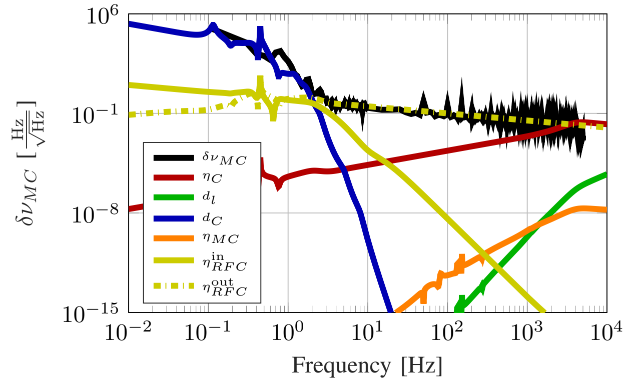
$$L_{\text{cav}} = N \cdot \frac{\lambda}{2}, \tag{1}$$

with L_{cav} the cavity length in m, λ the wavelength of the laser in m and N an integer number. Both the cavity length and laser frequency fluctuate several orders more than the required stability andare therefore actively controlled in a control system of three nested loops, each highlighted by a colored rectangular box in the block diagram below. The performance variable, the laser frequency fluctuations $\delta\nu_{\text{MC}}$, is influenced by all three loops and is furthermore subject to different disturbances coupling to the output, making it difficult to identify which controller to optimize and how.



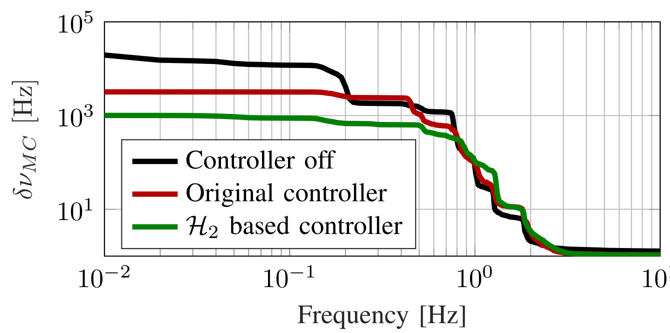
B. Approach

The approach constist of two steps. First, a Dynamic Error Budget (DEB) is developed, which consists of a spectrum of the error together with the closed-loop contributions of the modelled disturbances. This DEB is used to identify the limiting disturbances as well as how to tune the controllers to minimize this coupling. Second, the DEB is used as weighting in $\mathcal{H}_2$ synthesis to obtain a controller that minimizes the RMS of the performance variable.



C. Experimental results

The $\mathcal{H}_2$ based controller is implemented on the full Virgo detector to compare the experimental performance. The $\mathcal{H}_2$ based controller (**—**) outperforms the original controller (**—**) in terms of Root-Mean-Square (RMS) error by a factor three. In this talk, we will present a systematic design method using dynamic error budgetting and $\mathcal{H}_2$ synthesis to derive the presented control design and further elaborate on the experimental results.



References

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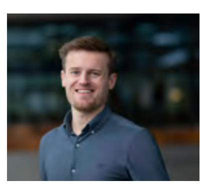

Mathyn van Dael received the MSc. degree in System and Control from the Eindhoven University of Technology, in 2021. Currently, he is pursuing a Ph.D. degree at the department of mechanical engineering at the Eindhoven University of Technology. His research is focussed on improving Gravitational Wave detectors through advanced control methodologies.