Precision Control for Gravitational Wave detectors

M. van Dael[1,2], G. Witvoet[1,3], B. Swinkels[2], T. Oomen[1,4]

[1]Eindhoven University of Technology, Control Systems Technology, the Netherlands

[2]Nikhef, Amsterdam, the Netherlands

[3]TNO, Department of Optomechatronics, the Netherlands

[4]Delft University of Technology, Delft Center for Systems and Control, the Netherlands

m.r.v.dael@tue.nl

Abstract

Gravitational Wave (GW) detectors are state-of-the-art mechatronic systems that can measure spatial distortions in the order of 10^{-18} meters. Two GW detectors that are currently operational are LIGO [1] and Virgo [2], both of which have already measured GWs, with the first one being measured in 2015 [3] resulting from the collision of two black holes. These detectors are large-scale interferometers that consist of many mirrors, some of which are several kilometers apart. Control has a fundamental role in the operation of these detectors as the mirror positions have to be controlled with microscopic precision.

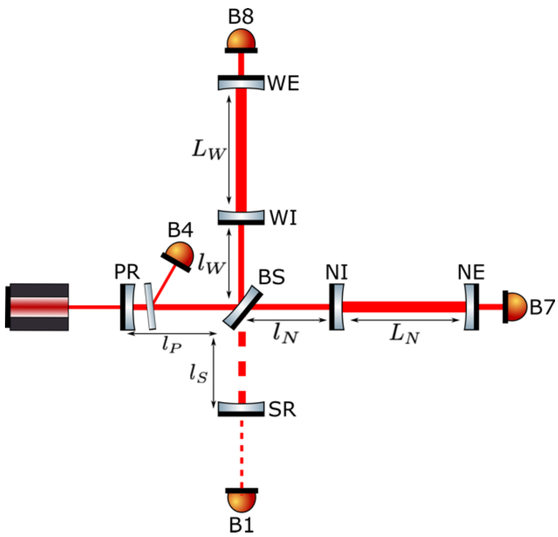

Figure 1 Optical configuration of Virgo

In Figure 1, the optical configuration of Virgo is shown. A laser (left most object) generates a beam of light that is split into two orthogonal directions (upwards and to the right) by the Beam Splitter (BS). The beams of light are reflected back by the end mirrors (WE and NE) to interfere at the BS, generating an interference pattern that is measured by the B1 photodiode. This interference pattern is a function of the difference in length between the two arms ($l_W + L_W, l_N + L_N$) and the sensitivity of the detector with respect to the amplitude of a GW scales linearly with the length of these arms. These arms are 3 kilometers long in the case of Virgo [2], with the choice of length for these arms thus being trade-off between sensitivity and cost. To give a sense of the level of precision in GW detectors, the required residual difference in length between these two arms when no GW passes is 1×10^{-16} RMS.

Additional mirrors (PR, SR, NI and WI) are added to improve the sensitivity of the detector to a GW, forming in total 5 degrees of freedom that have to be actively controlled with microscopic precision to maximize the detector sensitivity. These degrees of freedom are controlled using a decentralized feedback system that derives error signals through the measured powers on the photodiodes [4] and actively corrects the individual mirror positions. Traditionally, these decentralized controllers are designed for scalar systems.

A key challenge is that these loops exhibit non-negligible interaction that varies over time, resulting in a loss of performance and potentially stability issues. The aim of this abstract is to provide a full multivariable analysis and its consequences for decentralized control design. In Figure 2, three measurements of the MIMO plant for 3 of the 5 degrees of freedom are shown, with the off-diagonal terms shown to exhibit time-varying behavior. The main contribution of this work is to prove the relevance of interaction in this system and derive a design approach that explicitly addresses the time-varying behavior of the interaction terms.

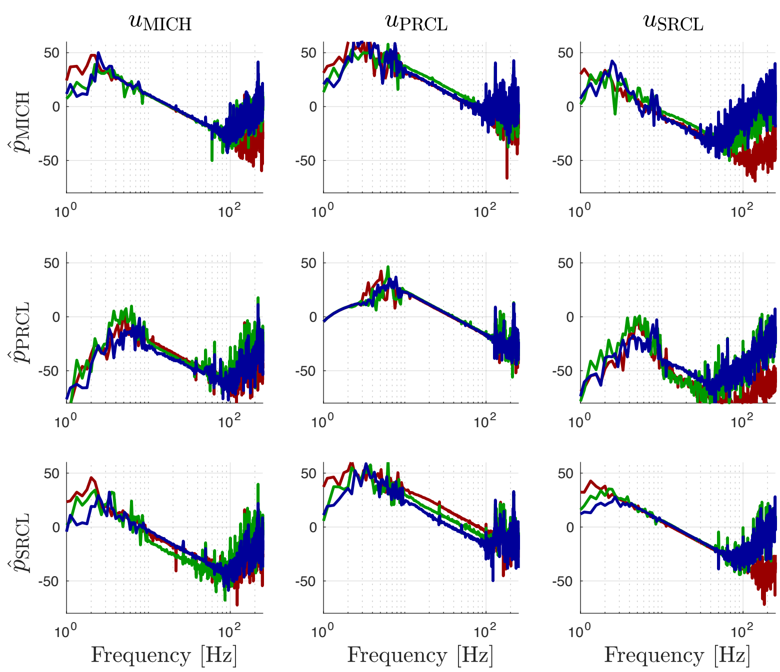

Figure 2 Magnitude plot of Frequency Response Matrix (FRM) of the plant for the three degrees of freedom (which are commonly referred to as MICH, PRCL and SRCL) that varying levels of interaction. The three different colors represent measurements of the FRM taken at least a week apart.

In conclusion, interaction is a major challenge in the design of decentralized controllers for some of the loops in GW detectors. A systematic design procedure is therefore provided which also deals with the time-varying behavior of the interaction terms. Based on this design procedure, a new control design for one of the loops is presented together with experimental verification of the controller performance on Virgo.

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