Electronic hardware and software development for the Advanced Virgo EPR squeezer

Mateusz Bawaj[1], Martina De Laurentis[2], Sibilla Di Pace[3,4], Alberto Gennai[5], Imran Khan[6,7], Ettore Majorana[4], Luca Naticchioni[4], Catherine Nguyen[8], Diego Passuello[5], Valeria Sequino[9], Fiodor Sorrentino[9], Marco Vardaro[10] and Jean-Pierre Zendri[11]

[1] INFN, Sezione di Perugia, I-06123 Perugia, Italy
[2] Università di Napoli “Federico II”, Complesso Universitario di Monte S.Angelo, I-80126 Napoli, and INFN Sezione di Napoli, Italy
[3] Università di Roma “La Sapienza”, I-00185 Roma,Italy
[4] INFN Sezione di Roma, I-00185 Roma, Italy
[5] INFN Sezione di Pisa, I-16146 Pisa, Italy
[6] INFN Sezione di Roma Tor Vergata, Italy
[7] Gran Sasso Science Institute, I-67100 L’Aquila, Italy
[8] APC, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France
[9] INFN Sezione di Genova, I-16146 Genova, Italy
[10] Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, and INFN Sezione di Padova, Italy
[11] INFN Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy

mateusz.bawaj@pg.infn.it

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Abstract

In this paper, we introduce the work on hardware and software built to manage the optical bench which hosts the optical squeezer source at the Virgo site in Cascina. In the past, the experimental setup implemented frequency-independent squeezing and it will be soon reconfigured in order to implement frequency-dependent squeezing via EPR entanglement for Virgo gravitational-wave detector. Furthermore we introduce an idea of automation for this prototypic subsystem in order to deliver a compact and robust apparatus which does not require surveillance of an operator.

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1 Introduction

Quantum Noise (QN) is a phenomenon which gives high contribution to the overall noise in the advanced interferometric Gravitational-Wave Detectors (GWDs). In the previous interferometer generation, the most relevant QN component was dominating in the high frequency region (300 Hz–10 kHz) of the detection band. This component of noise was attenuated by injection of optimal vacuum squeezed state [1]. In fact, Virgo Scientific Collaboration has already implemented Frequency-Independent

Squeezing (FIS) injection to the readout port of Advanced Virgo and reported improvement of the sensitivity curve of around 3 dB [2]. Currently, the Collaboration focuses on the work on the Frequency-Dependent Squeezing (FDS) injection using a Filter Cavity (FC) which will reduce QN either in the high and low frequency range. At the same time, Virgo Squeezing working group is studying a possible alternative way of producing frequency–dependent squeezed states without the use of FC. The mechanism of FDS without filter cavity, called Einstein–Podolsky–Rosen (EPR) squeezing, was theoretically proposed by Ma et al. [3] and subsequently demonstrated feasible by scientific group from ANU and Hamburg using a proof-of-principle setup [4]. At the moment, development facility for the production of squeezed vacuum at EGO/Virgo site is being adapted for the preliminary experiment on the EPR. This task is carried by the INFN group from Naples and Genova in collaboration with APC. The experiment represents a first step toward implementation of the new squeezing generation technique. For the purpose of the project, INFN group from Perugia together with groups from Pisa, Padova and Rome have been developing various types of photo-detectors and software based on Finite-State Machines (FSMs). In this paper, we overview the current state of work on the facility and we summarize in details the tasks related to the development of electronics and software for implementation of EPR squeezer. In particular, we focus on the engineering of analogue electronics for cavity locking and squeezed state measurement. We conclude by explaining the near future steps: FSM application scheme, noise hunting and operator independent lock acquisition.

There are three main motivations for this work. In principle the setup must be as accessible as possible to scientists from various fields of expertise. Thus, its handling must not require any complex operation on the feedback controls, like tuning or calibration. This approach is a first step to minimize necessary human interaction with the subsystem and can be obtained by its automation. Accurate automation will also help us in accomplishing the second goal which is the maximization of the subsystem Quality of Service (QoS). Last but not least, we want to reach the low noise characteristics and keep the subsystem compatible with Virgo infrastructure. We describe below the system developed using custom built devices and various devices built for Virgo.

2 EPR squeezer design assumptions

From the optical design of the EPR squeezer shown in Figure 1, we inferred the control system design requirements. In total, we need fourteen feedback loops of various kind: two Optical Phase-Locked Loops (OPLLs) to lock lasers in frequency; two locking loops for non-linear crystal cavities and four for Mode-Cleaner (MC) cavities longitudinal lock, implementing Pound–Drever–Hall technique (PDH); one Proportional–Integral–Derivative controller (PID) for Mach–Zehnder interferometer for light intensity stabilization, two PIDs for Coherent Control (CC) loop for squeezing phase stabilization [5] and yet another three for temperature control loops for non-linear crystals and etalon. Several of these devices need to be fed with a reference frequency. For this purpose we use a custom made 14-channel, synchronous Direct Digital Synthesis (DDS) generator. Actuation on the cavity mirrors is done using high-voltage piezoelectric actuators. We use a custom built amplifier to drive them. In the next two paragraphs we describe the hardware and the software structure of the system.

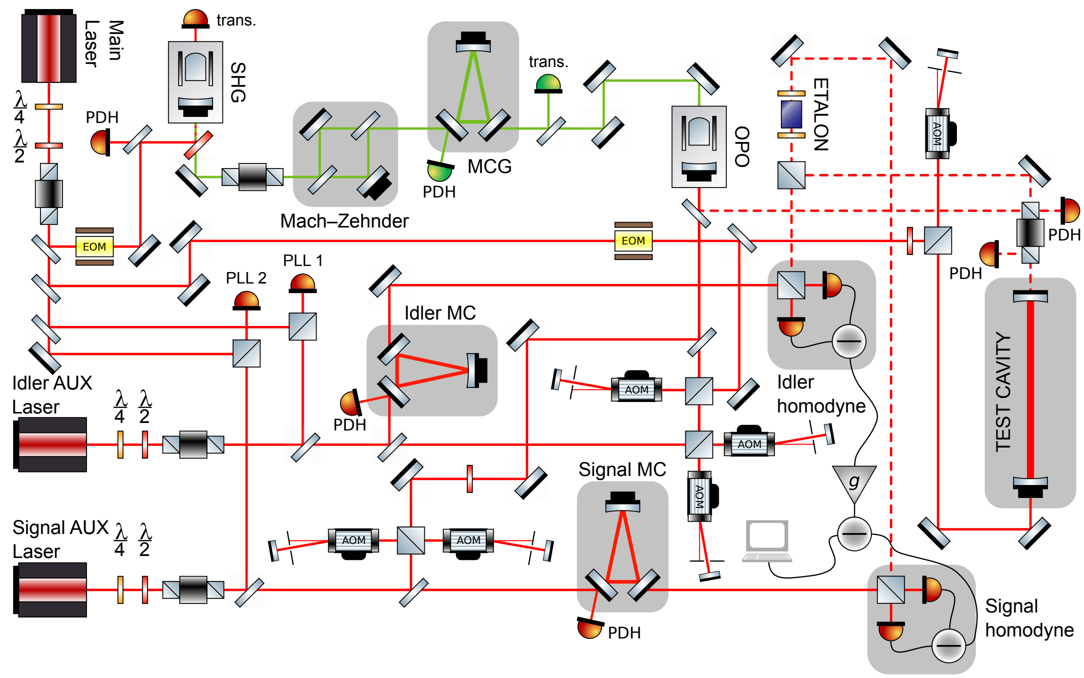

Figure 1: Generic scheme of the optical design in the EPR experiment with locking and automation details. In the figure are indicated optical cavities with corresponding photo-detectors for locking, OPLL photo-detectors, electro-optic modulators for PDH sidebands generation and homodyne detectors for conditional squeezing detection.

3 Hardware system architecture

Hardware architecture of the electronic system, controlling the optical bench, is shown in Figure 2. For better understanding, the scheme should be read from the left to the right and from the top to the bottom. Symbols in the left column depict optical cavity longitudinal lock, while symbols on the right depict OPLL components. Fast demodulated photo-diode is shared between the two chains since it provides signal for both. The loops are implemented using analogue and mixed-signal devices. The latter: DDS, Digital Signal Processing (DSP) card, OPLL board and temperature PID are managed by a Personal Computer (PC) via digital links.

In the system, there is one reference frequency source synchronizing all DDS channels. Sine forms generated by the DDS are used to: drive Electro-Optic Modulators (EOMs) and demodulate signal from the corresponding photo-detectors in the PDH loops; give reference frequency for phase detectors in the OPLL and in the CC loops.

Beneath we report improvements introduced in the electronic equipment. In order to provide a reliable reference frequency for the system, we built a PLL stabilized Voltage-Controlled Oscillator (VCO) based reference clock source using ADF4360-7 development board. Configuration of the VCO generator is handled by a micro-controller which monitors constantly the PLL-lock status and reacts in case of failure. Moreover, the micro-controller uses its own watchdog to further increase the reliability of the running firmware.

High voltage drivers used to drive piezoelectric actuators in optical cavities are linear amplifiers.

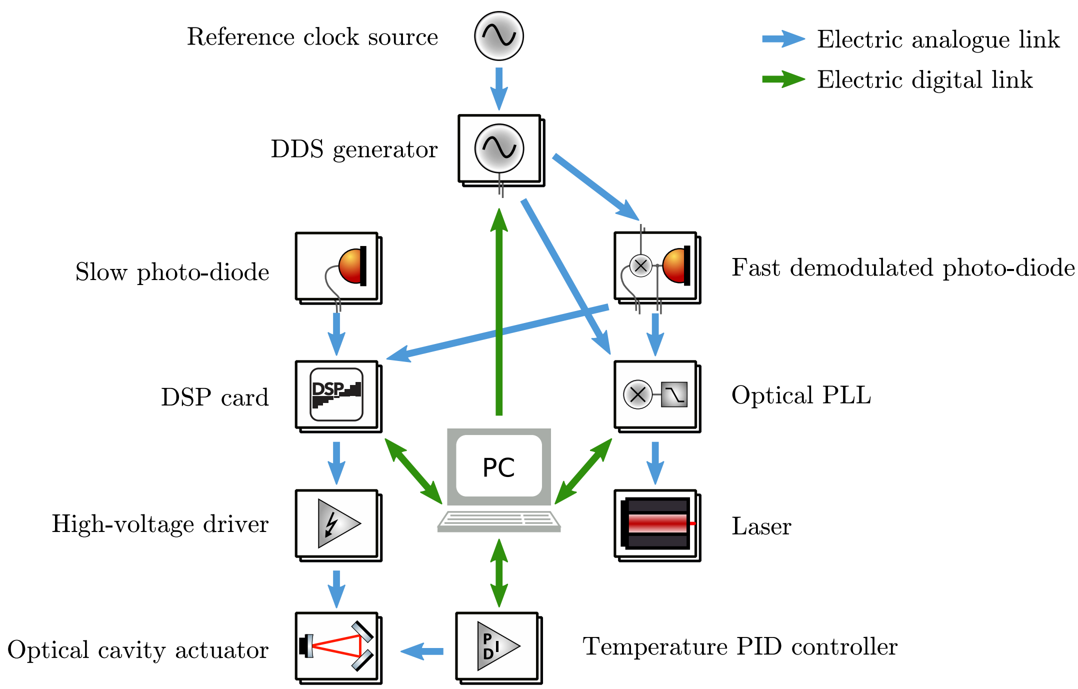

Figure 2: Hardware architecture scheme shows devices in the system and physical links between them. Single reference clock source feeds synchronous, multi-channel DDS generator. Loop implementing PDH technique is shown schematically on the left. In this loop two photo-detectors, indicated as slow and demodulated, are involved. Signals coming from the detectors are digitalized and processed on the DSP card which provides a correct, frequency dependent gain. Correction signal is then sent to the high-voltage driver and to the piezoelectric actuator. Optical PLL is depicted on the right. This loop uses direct output from the fast photo-detector and sends it to the OPLL board which implements analogue filter for laser's piezo and digital PID controller for laser's temperature. In the figure electric links are indicated by arrows, its colour indicates the type of connection while arrowhead indicates the direction of information flow. Symbol placed inside a pile symbol depicts that there are many devices of the kind in the system.

We introduced internal reference voltage modification to lower their output noise. We suppressed power line noise by introducing a high-voltage stabilizer in the power supply. The use of the stabilizer let us decrease filtering capacity and at the same time maintain the output voltage pulsation low. After the upgrade we obtained power supply output noise $E_{\text{out}} = 3\,\mu\text{V}/\sqrt{\text{Hz}}$ at the corner frequency 200 Hz measured with 30 mA on resistive load. Amplifier's output noise is now $V_{\text{RMS}} = 4.85\,\mu\text{V}$ in the operation bandwidth from 1 Hz to 20 kHz.

Existing fast photo-detectors, which implement on-board demodulation, were redesigned to provide signals with differential outputs. It makes them robust against the noise induced in wires connecting the optical bench with 19″ racks. We used an existing Virgo Data AcQuisition (DAQ) interconnection electric standard. Input preamplifier of the photo-detector was reviewed and its bandwidth was increased to 80 MHz when using 0.5 mm diameter photo-diode and 120 MHz for 0.3 mm diameter.

Changes concern also the homodyne detector. We introduced modifications to the electronic circuit design and we improved mechanical stability. Both lead to better noise characteristics and robustness of operation. We measured 82 dB of Common-Mode Rejection Ratio (CMRR) at 270 Hz.

Lock acquisition stability was improved by software modification and automation. This argument is a topic of the next section.

4 Software system architecture

Before describing the software improvements, lets have a closer look on the Information Technology (IT) architecture shown in Figure 3. In this figure all devices shown in the dashed frame are configurable by software. At present, several of them are configured via Tango server [6] while others are individually interfaced with a PC. Considering that Tango is supported by Virgo infrastructure this is a temporary state. Eventually all devices will be configured via Tango server. The main advantages of using Tango server is its compatibility with Virgo and the possibility of simultaneous work of scientist on various sections of the optical bench.

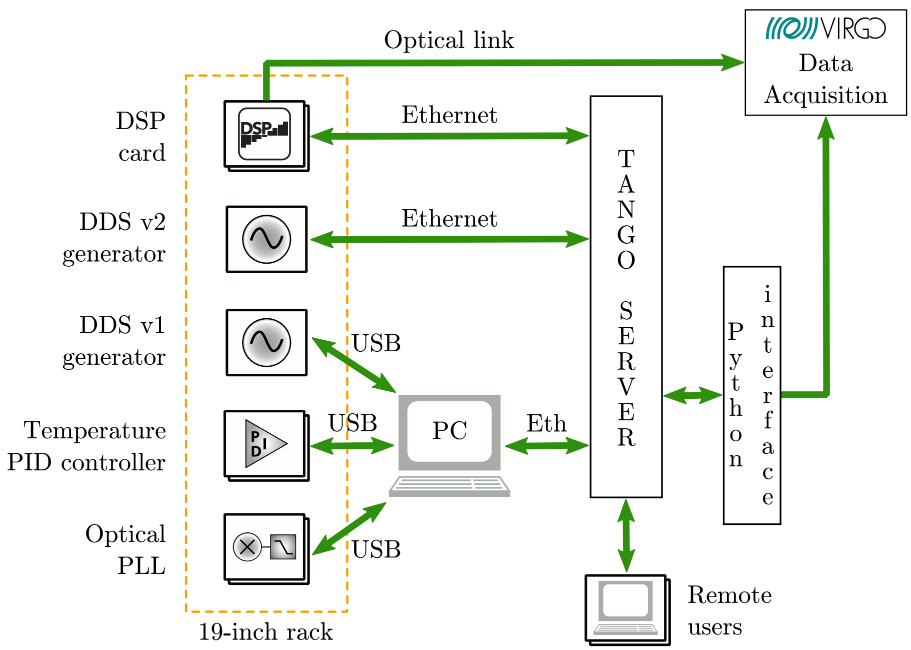

Figure 3: Software architecture scheme. In the scheme, electronic devices are shown in the dashed rectangle. Outside of the rectangle there is IT infrastructure. Digital connections are depicted as arrows.

Software in the system is divided in two categories; firmware and PC software. Firmware is present in each configurable device but we will briefly describe only the firmware of the DSP card as it is the most interesting from the point of view of automation. We use DSP accelerated DAQ system designed for processing digitalized analogue signals for controls of the super attenuator. The DAQ is a distributed system composed of rack crates and relative servers. Crates are connected to Tango, firmware distribution system and time distribution system for synchronization. Each crate can host up to twelve DSP cards. Each DSP card, takes input signals from on-board Analog-to-

Digital Converters (ADCs) or from other boards placed in the same crate via back panel. Signals are processed by a dedicated piece of code (firmware) compiled by a custom Software Development Kit (SDK). Output of the firmware calculation can be sent either to the on-board Digital-to-Analog Converters (DACs) or to any other card inside the crate. SDK supports math operations and eases design of digital filters. The newest version of the SDK supports implementation of FSMs.

We exploit the natively supported digital filters and FSMs in the firmware which we wrote in order to lock automatically feedback loops. In the system, we can distinguish loops between; loops for optical cavities which use PDH technique and loops for Mach–Zehnder (MZ) and CC which use PID controller. FSM implementation differs in both cases but both of them gives the same functionality: when initialized the FSM calibrates itself and after the calibration it can be controlled by the state of one variable. The value determines a desired state of the cavity that the FSM will attempt to reach by autonomous operations.

5 Conclusions

In this paper, we reported necessary upgrades in the electronic system managing the Virgo R&D squeezer. We introduced to the system a robust reference clock oscillator, we lowered the noise of the high-voltage section and we modified the fast photo-detectors to make them electrically compatible with Virgo standards. Finally, we improved the homodyne detector stability. Currently, we are studying a new architecture of software in order to increase automation by governing FSMs by external software from a PC. In the near future, we will duplicate our devices to satisfy the requirements of the EPR optical layout. Implementation of the EPR requires extension of the FSM logic on the additional hardware. Further, we will commission the new software and perform measurements of the QoS.

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