# Controls Workshop

- Participation
- Workshop mode
- DCC page
- Summary of the four sessions
- Perspectives

# GWADW2016 - Impact of Recent Discoveries on Future Detector Design

## Angular control

↓ **Challenging, noise limiting, optimization, integration in early design**

## Local and global control

↓ **FF and FB advanced techniques, stability, sensor noise, cross coupled dofs.**

## Learning algorithms for tuning global IFO control

↓ **Path forward for optimal control**
**Promising techniques, non-linear correlations**

## Controls considerations for next generation detectors

**List of control problems and options, integration in the early design, working document**

# 1) Angular control

Summary of mechanisms of L2P and P2L couplings, noise couplings

Can we use the local damping to smooth the Sigg-Sidles resonances so that we don't need to change global control filters as a function of laser power?

**Discussion:**

- WFS noise
- Loops design (room for optimization)
- Feedforward length to angle to reduce L2P
- Beam centering , DC can be improved now that dP/dteta is solved, with addition of third layer of ISS loop
- AC: L2P decoupling (in loop identification?)
- FB optimization, cost functions to minimize angular motion, optimize poles and zeros location of the control loop (MCMC, particle swarm…)

**Outcome:** there is a relatively clear path forward, and hope to reduce the 10-30 Hz noise

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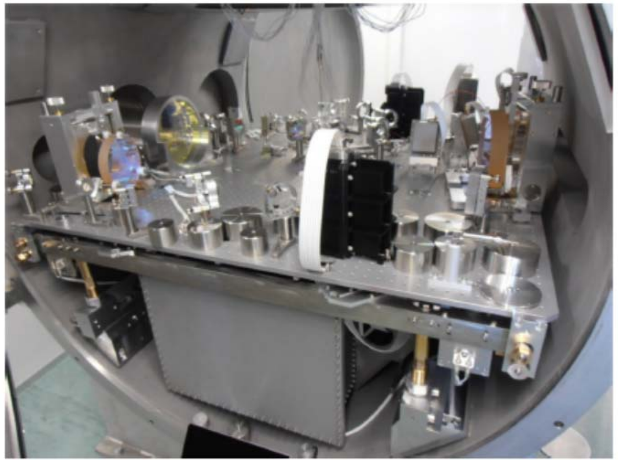
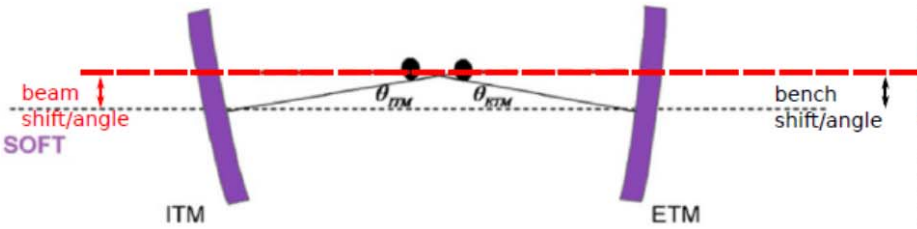
**Angular control of Advanced Virgo suspended benches**
Michał Was

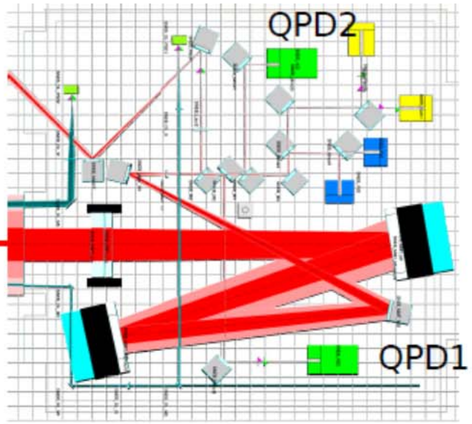


**Control scheme**
**Use of redundant sensors for cross calibration**

**Performance optimization:**
- Global cost function
- Better sensing

**Discussion:**
- Trans-Mon interaction with global control
- Control relative to test mass
- Involved in the soft loop
- Novel techniques of oplev from transmon to ETM



# FB optimization

**Motivations**

- More gain, margin, less noise -> cost function
- Faster design, plant changes

**Discussion:**

- Past workshops, tutorials, end to end examples, repository
- Opening CSWG membership to Kagra
- Coordination with collborators (Berkley, Google…) , growing interest to collaborate with us. Good opportunity.
- Continuing investigation, to be organized within the CSWG

# 2) Local and global control

**Present and future of Superattenuator control system**
Valerio Boschi

**Present Superattenuator control system**

**Near term future (< 1 yr)**
System identification, Optimal control, Adaptive control

**Long term future (> 1 yr)**
Tilt Control, New Sensors, MIMO damping

**Discussion:**
- Robustness of Kalman filtering against plant parameters changes related to global control and radiation pressure
- Comparison of sites ground motions, significant differences (L1, H1, V, I, K)
- Implication for the controls as we implement Virgo style seismic isolation in kagra, and LIGO isolation in India

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**Hopes and Dreams: One Transfer Function Fitting Program to Rule Them All**
J. Kissel

**Pros and cons existing tools:**

Seismic using **N4SID**, Low-Q, MIMO Plant fi6ng for Noise Modeling

Suspensions using **Home-brewed Matlab** - Parameter estimation

Interferometer Control (**using VectFit**), High-Q, Transfer-func4on Ra4os for DOF decoupling

Calibration using pre-packaged **Python,** Bayesian parameter estimation

Calibration using **LISO**, Electronics poles & zeros with uncertainty estimation

**Discussion:**
- Discussed additional tools (PEM, SysID toolbox, MISO wrapping around LIGO…)
- Would be convenient to have one single package, but no clear path forward
- Still was an excellent review of tools available

**IFO robust configuration**

**Earthquakes: introduction, goals, discussion. Outcome:**

**1) Seismon, terrmon, arrival and amplitude predictor**

**2) Threshold**
O1 analysis, statistics, predictor confidence levels
One single indicator, EPICS vriable, clear alarm

**3) Configuration**
Inertial control blend, local damping (less cutoff, more gain) , angular control
More robust (more noise) to keep the IFO lock
Steping back in the locking process (using ALS)
Automation

**4) Preliminary tests**
Capability to switch configuration smoothly
Emulate earthquakes (Inject wave form at the upper stage)

**5) Collaboration across the community**

# 3) Learning algorithms

**Deep Machine Learning**

- What problems do we want to solve which we cannot do yet?
- Mystery noise, tilt-horizontal, angular noise,…
- What problems are already solvable but quite difficult?
- Global feedback design, glitch classification
- Are there techniques out there?

**Nonlinear Regression**

- Volterra (1890) series representation; expanded by Wienera tool based on SIleNTe (Sistem identification Non Linear Techniques) based on Volterra series to cancel out noise for Virgo data.
- beyond linear regression; includes 'by-hand' nonlinear terms (e.g. higher order polynomials)
- kernel based methods, self generate basis
- L1 & L2 norms used to reduce complexity / sparseness / overfitting

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**Discussion led by Elena Cuoco on the use of machine learning for glitch classification**

Very useful to reduce parameter space

**Machine learning libraries:**

General tool: from preprocessing to SVM, DT, RandomForest...:
http://scikit-learn.org/stable/

Very useful for regression problem:
https://xgboost.readthedocs.io/en/latest/

Neural networks and deep learning
https://mxnet-bing.readthedocs.io/en/latest/
http://deeplearning.net/tutorial/

Competitions on this platform:
https://www.kaggle.com/

“Maybe  we can prepare a data set which can be useful for your purposes and ask to data scientists to find solutions, writing code just for knowledge.

In Virgo, I'm trying to setup a small group interested in ML techniques, maybe we can share our efforts. “

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**Example of applications (by Rana):**

- Use the flashing time series to learn how to lock the interferometer. Multiple error signals linearized.
- Use PEM signals to predict glitches
- Array of accelerometers/microphones to synthesize the scattered light noise
- Diagnose noisy states of interferometer before the operators. Send SMS to appropriate scientist.
- Predict imminent failure of facility systems with PEM + HVAC sensors. (power lines, weather, HVAC vibrations)
- Slow trends in backscatter or other couplings indicate device failures. (e.g. photodiodes, DACs, wires, laser alignments)
- help operating decisions

**Noise hunting:**

Many Noise problems eliminated

- All linear regression combinations checked
- Now testing some bilinear methods by brute force creation of pseudo channels
- Think we need more fully nonlinear estimator

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**Review of ML techniques:**

- Unsupervised Learning
- only has input data (no target)
- Supervised Learning (includes all of MS Azure)
- has both input and output (e.g. PEM & h(t))
- Reinforcement Learning
- given knowledge of desired output states
- algorithms learn how to move to desires based on inputs

**And tools**

Microsoft Azure Machine Learning for classification, regression, clustering, anomaly detection

Google tensor flow

**Some Useful Links**

- http://usblogs.pwc.com/emerging-technology/demystifying-machine-learning/
- https://www.udacity.com/course/machine-learning--ud262
- https://azure.microsoft.com/en-us/documentation/articles/machine-learning-algorithm-choice/
- http://openclassroom.stanford.edu/MainFolder/CoursePage.php?course=MachineLearning
- https://www.quora.com/What-is-the-difference-between-L1-and-L2-regularization

## 4) Controls considerations for next generation detectors

**2G+: Improved optical mode matching, adaptive mode-matching**

**Discussion topics:**

- Actuators: ROC only, ROC & Astigmatism, Macroscopic translation?

- Sensing: Poor observability of mode parameters (waist size/position or Gouy phase)? Are existing wavefront sensors adequate? Should we add bullseye sensor(s)?

- Mode matching is a nonlinear system with nonlinear cross-couplings. Genetic algorithm for optimization (esp. if HOM are controlled)? Predictive model (e.g. Kalman filter) to accommodate thermal transients due to lock losses?

- WFS adequate? Hartman sensors?

**Outcome, highlights of the discussion:**

- Sensing the temperature field better than adding wavefront sensors

- ROC control for Parametric instability? Virgo? G-factor?

- Thermal control can be simplified by a better design (OMC example). Redesign of cavity optics would make the actuation matrix simple.

- Phase camera used at Virgo, not a good AC sensor

- Improving the ASC sensors

- Spot defect technique to center the spot on the mirror (Baz)

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**2G+: Frequency-dependent squeezed light injection**

**Discussion topics:**

Any unique or new controls challenges?

**highlights** More controls, more alignment. Geo is working on ideas to align to the OMC.

**2G+: Balanced Homodyne readout, beacon alignment of the OMC (control without a LO field)**

**Topics:**

Solved controls problem? Just need to demonstrate?

What sensor/measurement or metric is used to adjust the LO phase in BHR?

Perhaps machine learning techniques can be applied to achieve these adjustments?

**Discussion outcome:** Phase control, calibration lines…

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**2G+: Lower thermal noise (lower loss TM coatings or larger beams)**

**Topics:**

**-** Is ALS dichroic coating a significant coating design constraint?

**-** ALS design to accommodate non-optimal finesse?

**-** Suspension point interferometer instead of ALS?

**Discussion outcome:**

- Locking at 1.5um, combs, 1.3 um
- SPI does not offer advantages over ALS. Can still be useful in the vertex.
- VIRGO+, Folded recycling cavities, need facility extensions??
- Parametric instabilities??

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**2G+: Lower TM bounce mode frequency & reduced suspension thermal noise (longer suspension, thinner fibers)**

**Topics:**

Opportunity for design adjustments

**Discussion outcome:**

- Suspension design adjustments with global control considerations?
- Insure all dof are observable and controllable (e.g bounce & roll)
- Consider implementing redundant sensing and control to increase reliability & improve estimated
- Design solutions to minimize pitch/length coupling

## 2G+: Real-time servo tracking a source/signal

**Discussion outcome:**

- Adjusting SRC detuning? Switch to narrow-band configuration for BNS?
- Adjusting SRM transmission? (with a variable transmission RM?)
- Adjusting LO phase in BHR?
- Perhaps machine learning techniques can be applied to achieve these adjustments?
- Detuning versus squeezing, needs better study

# 4) Controls considerations for next generation detectors

**Voyager:**

aLIGO, plus A+, plus Heavier (150kg) Silicon TMs @123K, with Si ribbons, ~2.0 micron wavelength, Low temperature (123K) TMs

- Parametric instability (0.8MW to 3 MW), many modes unstable. Thermal lensing? Online identification and damping?

**Cosmic Explorer**

Longer filter cavity , Longer suspension, Larger beams on TMs.

**Discussion outcome:**

- By definition, CE is (was?) no new technology, 'just' longer arms, …
- Angular stability tradeoff with g-factor for long arms. Is there a driver to improve angular stability, or will we stick with demonstrated aLIGO performance to date?
- End to end modeling. Useful. Still need simplified models. Require dedicated support.
- Cindiser carrefuly the design of Facilities to minimize local disturbance (AC, pumps, chillers, wind…)

# 4) Controls considerations for next generation detectors

**General Considerations**

Complete observability and controllability for all degrees of freedom (dof)

- Higher upfront cost, but less cost during commissioning
- Helps with fault tolerance (graceful degradation)
- Can always abandon if not needed to reduce complexity and improve reliability
- e.g. Bounce & roll modes of the aLIGO quad suspension
- Other examples?

Improved data munging tools (more of a DetChar than controls issue)

- Imposing rigor and infrastructure for self-defined DAQ signals?
- Improved means to query database over broken lock stretches?

Improved transfer function fitting tools (including estimates of uncertainty)

- Leveraging off of the models for experiment/measurement design
- Using the (validated) models to extrapolate to unmeasured (or poorly measured) couplings or dofs

Sideband/modulation and readout scheme for Observable interferometer length dof. Sensing matrix for ET (G1500819), what about for A+, CV, CE …?

Same for angular dof?

Adequacy or shortcomings of current simulation models

Control & Data Systems (CDS) Architecture?

- Likely requires custom ADC & DAC designs, Low noise, high dynamic range, Projects could leverage off shared design & development?
- Continue to leverage off of HEP community (EPICS), or explore alternatives?

## Conclusion, perspectives

**- We swept a large variety of controls techniques and applications**

**- A number of them sound promising**

**- The Controls System Working Group will help organizing and coordinating the effort**

**- Involving KAGRA in this forum**

**- Motivated outside participations from experts in industry**

**- Common point of interest across instrumentalists, DetChar and data analysis groups**

To subscribe to the control system working group:

https://grouper.ligo.org/mailinglists/cswg

The CSWG electronic log:

https://alog.ligo-la.caltech.edu/CSWG/