Controls in Advanced Virgo: from Lock Acquisition to Lock Losses

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1. Introduction on Controls
2. Acquiring Control in Interferometers: Lock Acquisition
3. Improving Control in Interferometers: Noise Subtractions
4. Losing Control in Interferometers: Lock Losses
5. Machine Learning and Interferometer Controls: Possible Use Cases

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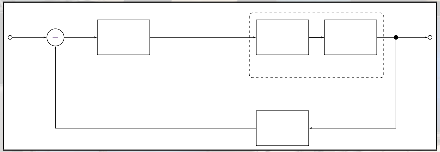
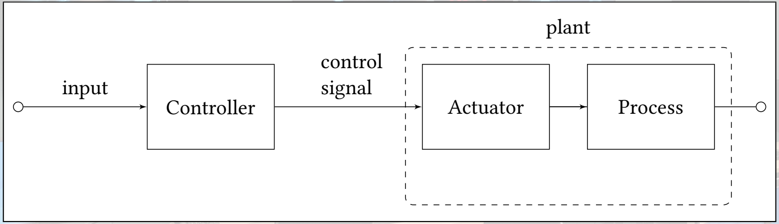
What is a Control System?

- A Control System is an ensemble of interconnected components designed to bring a physical process in a desired state
- Control Systems have been used for a long time, for both new and long-standing processes
  - motivation and goal may be constant over time
  - methodology and implementation can evolve rapidly
- Several types with different requirements and purposes
- Described by block diagrams



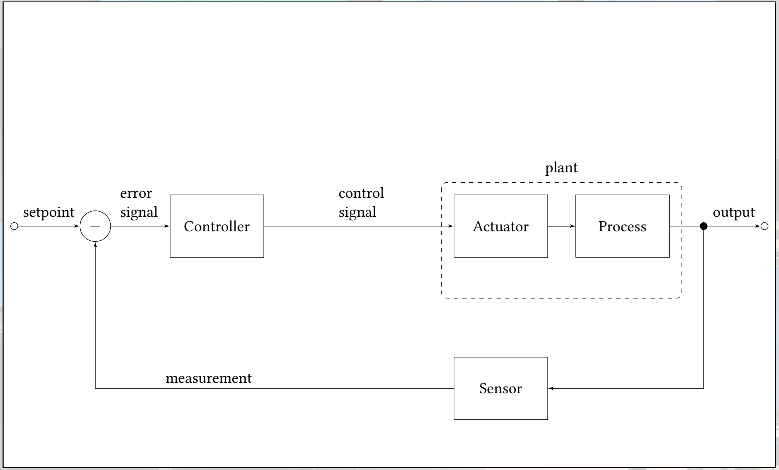
Three Classes (1): Open Loop Control



Open Loop Control:

- It drives the Process to a certain state
- It is *not* error-based
- No reading is done on the system

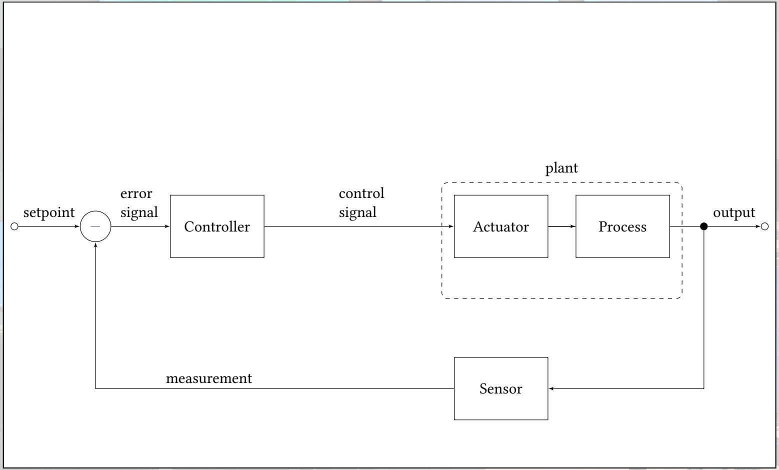
Three Classes (2): Feedback Control



Feedback Control:

- It is error-based
- It reads back the behavior of the plant
- It defines the working point of the system

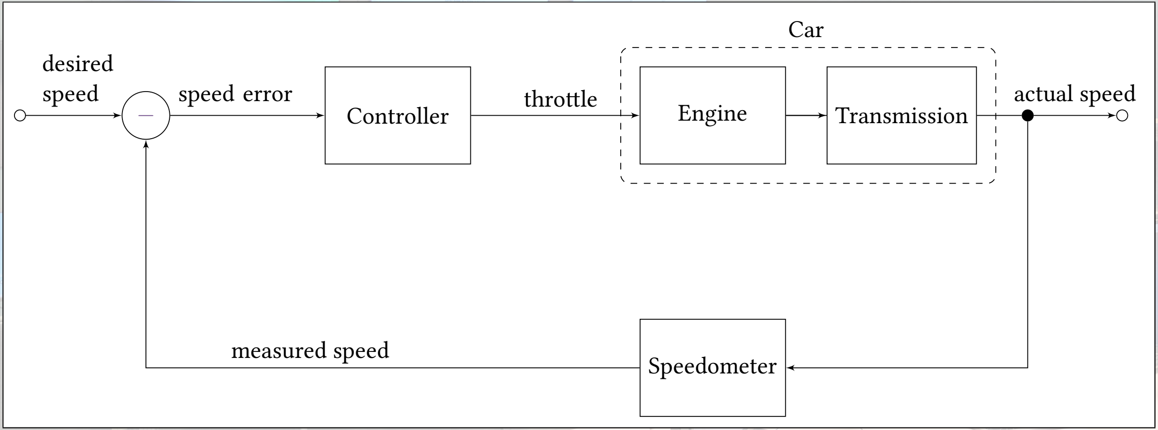
Requirements for a Feedback Control



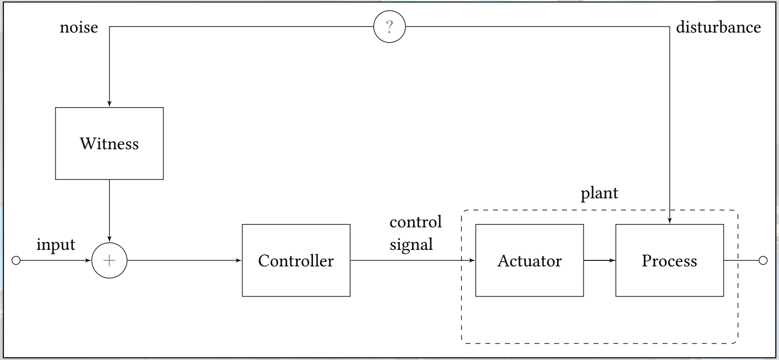
Requirements:

- **Stability**: the overall system must be stable
- **Tracking**: the output must track the input signal
- **Regulation**: system must not overreact to disturbance inputs
- **Robustness**: these goals must be met even in case in inaccurate modeling or changes in dynamics or environment

Example of a Feedback Control: the Speed of a Car



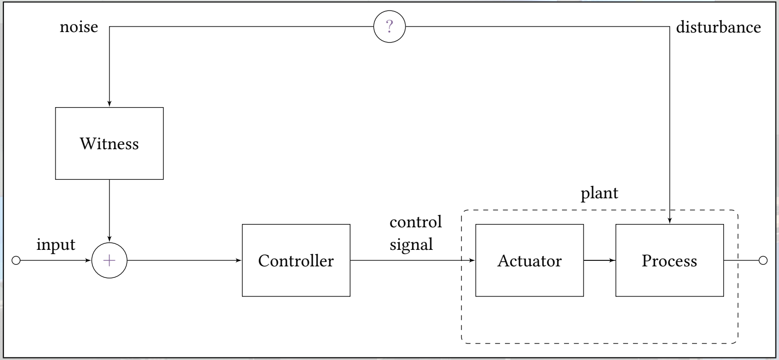
Three Classes (3): Feed-Forward Control



Feed-Forward Control:

- It reduces an *external* disturbance
- It needs a *witness*
- The input is not affected
- It is less constrained than feedback
- It needs very accurate modeling

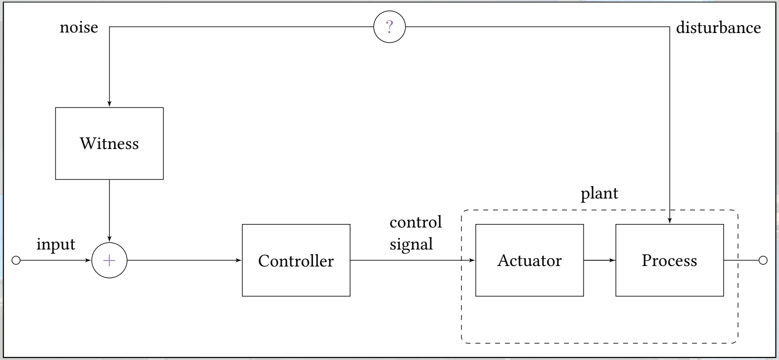
Feed-Forward Control: the Witness



Feed-Forward needs a *witness* of the noise to be reduced:

- The system must be set up in a way to be able to read the external disturbance *independently*
- Such witness must possibly have no other information
- The witness must be reliable over time

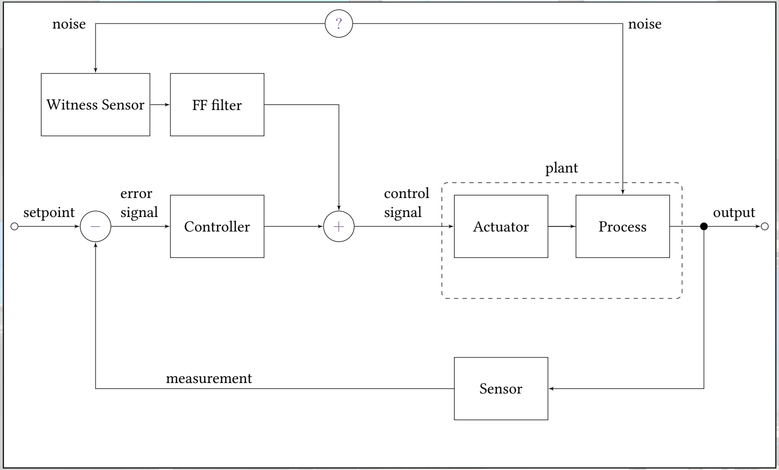
Feed-Forward Control: Operating Conditions



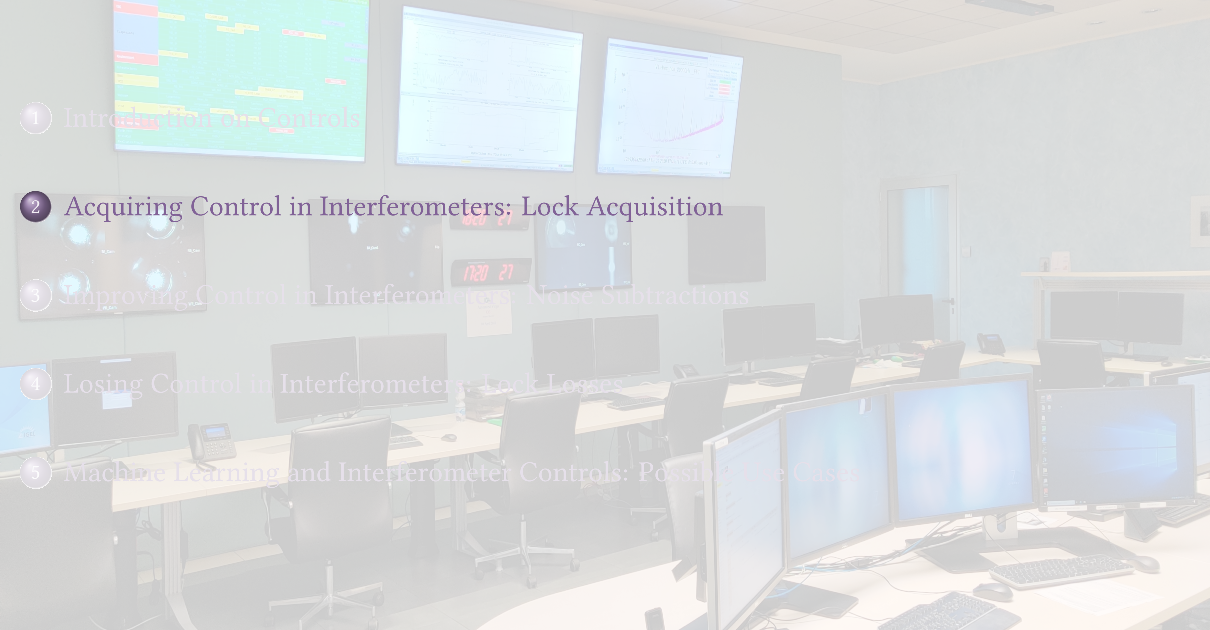
Fewer constraints than Feedback Control:

- There are no requirements (phase margin, etc...)
- A feed-forward is not "stable" or "unstable"
- The witness and the model define the performance
- The effect is the *reduction* or *amplification* of noise

Feed-Forward inside a Feedback Control

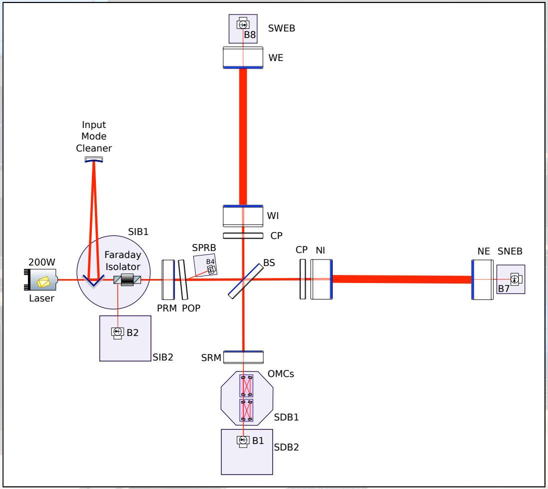


- Reduction of an external disturbance from a *in-loop* variable
- The relationship between noise and witness must be well known
- The relationship between noise and actuator must be well known
- A precise model is needed in order to build a performing filter



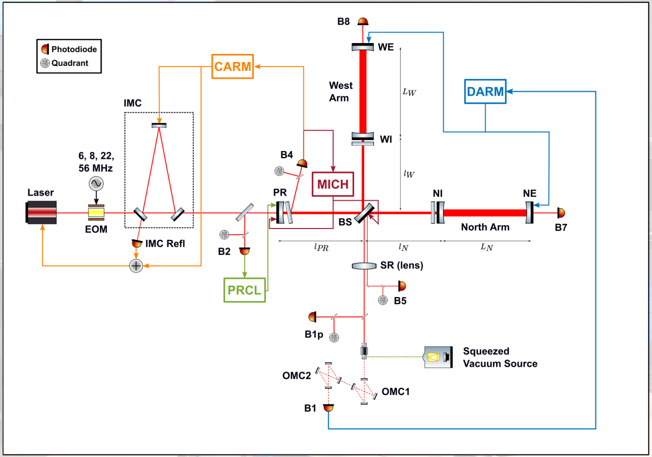
Advanced Virgo: a Gravitational Wave Interferometer

- Very complex opto-mechanical system, with several suspended mirrors
- Narrow operating point, defined by the *resonance condition* of several optical cavities
- Many auxiliary systems
- Must be considered a single entity



Global Longitudinal Degrees of Freedom (*O3* Run)

- MICH = $l_N - l_W$, the length difference of the short arms of the Michelson, it defines the interference condition
- PRCL = $l_{PR} - \frac{l_N + l_W}{2}$, the Power-Recycling cavity length
- CARM = $\frac{L_N + L_W}{2}$, the common, average length of the long Fabry-Pérot arm cavities
- DARM = $L_N - L_W$, the length difference of the long Fabry-Pérot arm cavities, sensitive to gravitational waves



Lock Acquisition

- When the interferometer is not controlled, the mirrors are free to move; their typical low frequency peak-to-peak motion can span as much as one wavelength ($\approx 1\,\mu\text{m}$), *if* the *Local Controls* (which use auxiliary lasers and Position Sensing Devices) are engaged, otherwise the motion is much higher

- Lock Acquisition: how to bring the system from a complete uncontrolled state to the final one, when all distances are tuned to the correct working point

- A *serial* procedure must be identified, and the control progressively acquired using one or more techniques

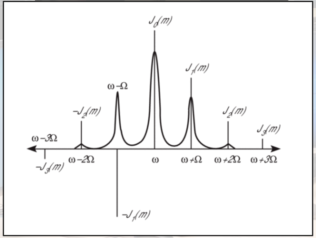
- There is the need to have viable error signals to be used for the controls

Phase Modulation

- Technique: phase-modulate the laser light
- Use of a EOM (electro-optical modulator), as a Pockels cell: a crystal with a tunable optical length via a driven voltage
- The EOM is driven with a sinusoidal signal which is converted in a variation of phase of the transmitted laser beam
- Generation of radio-frequency sidebands

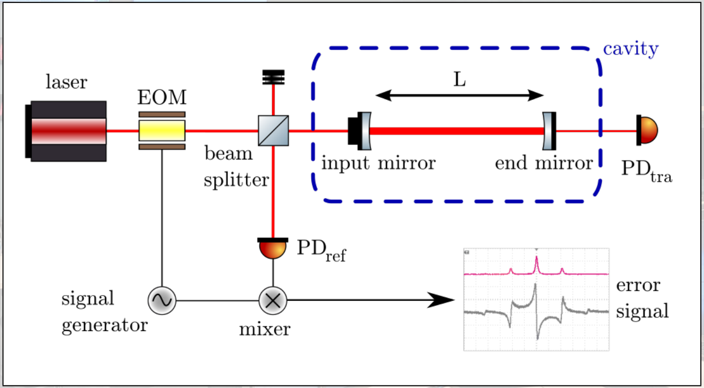
$$E_{\mathrm{inc}} = E_0 \, \mathrm{e}^{-i(\omega t + \beta \sin \Omega t)}$$

$$E_{\mathrm{inc}} \simeq E_0 \left[\mathrm{e}^{-i\omega t} + \frac{\beta}{2} \, \mathrm{e}^{-i(\omega+\Omega)} - \frac{\beta}{2} \, \mathrm{e}^{-i(\omega-\Omega)} \right]$$



The Pound-Drever-Hall Technique (1)

- Technique used in the '80s to stabilize a laser using a resonant cavity's length as reference
- It can be used the other way around: stabilize a resonant cavity length's using a laser as reference
- It is the main technique used in GW interferometers



The Pound-Drever-Hall Technique (2)

After the EOM, we have:

$$\begin{aligned} E_{\text{inc}} &= E_0\, e^{i(\omega t + \beta \sin \Omega t)} \\ &\approx E_0 \left[J_0(\beta) + 2 i J_1(\beta) \sin(\Omega t) \right] e^{i\omega t} \\ &= E_0 \left[J_0(\beta)\, e^{i\omega t} + J_1(\beta)\, e^{i(\omega+\Omega)t} - J_1(\beta)\, e^{i(\omega-\Omega)t} \right] \end{aligned}$$

where ω is the carrier's angular frequency, Ω is the EOM's modulation angular frequency, β is the modulation depth and J_0 and J_1 are Bessel's functions; therefore, the two sidebands have the angular frequency $(\omega \pm \Omega)$.
If the modulation depth is small, all the power is in the carrier field and in the *first order* sidebands; this means that

$$P_0 \approx J_0^2(\beta)\, P_0 + 2 J_1^2(\beta)\, P_0$$

The Pound-Drever-Hall Technique (3)

The reflected field in a Fabry-Pérot cavity has the form

$$E_{\mathrm{r}} = \frac{-r_{\mathrm{I}} + r_{\mathrm{E}}\, \mathrm{e}^{-i\phi}}{1 - r_{\mathrm{I}} r_{\mathrm{E}}\, \mathrm{e}^{-i\phi}} E_0 \equiv \varrho\left(\omega\right) E_0$$

where ϕ is the round trip phase.

Therefore, our reflected field is

$$\begin{aligned} E_{\mathrm{r}} = & \, E_0 \varrho\left(\omega\right) J_0\left(\beta\right) \mathrm{e}^{i\omega t} \\ & + E_0 \varrho\left(\omega + \Omega\right) J_1\left(\beta\right) \mathrm{e}^{i(\omega+\Omega)t} \\ & - E_0 \varrho\left(\omega - \Omega\right) J_1\left(\beta\right) \mathrm{e}^{i(\omega-\Omega)t} \end{aligned}$$

The Pound-Drever-Hall Technique (4)

The reflected power has three terms:

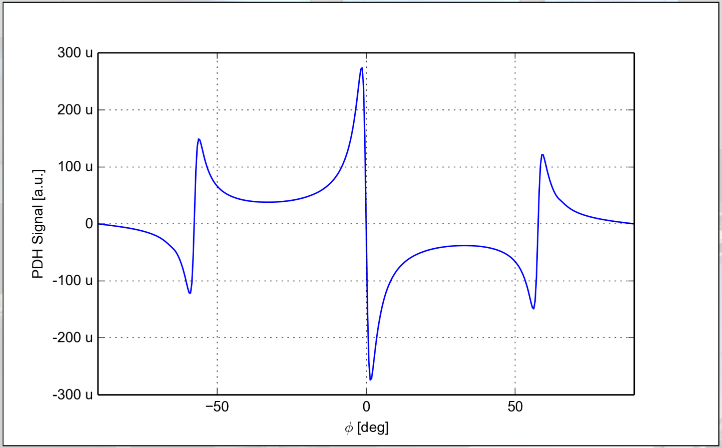
$$P_{\mathrm{DC}} \equiv P_{\mathrm{c}}|\varrho\left(\omega\right)|^2 + P_{\mathrm{s}}\left[|\varrho\left(\omega+\Omega\right)|^2 + |\varrho\left(\omega-\Omega\right)|^2\right]$$
$$P_{\mathrm{I}} \equiv 2\sqrt{P_{\mathrm{c}}P_{\mathrm{s}}}\Re\left[\varrho\left(\omega\right)\varrho^*\left(\omega+\Omega\right) - \varrho^*\left(\omega\right)\varrho\left(\omega-\Omega\right)\right]\cos\left(\Omega t\right)$$
$$P_{\mathrm{Q}} \equiv 2\sqrt{P_{\mathrm{c}}P_{\mathrm{s}}}\Im\left[\varrho\left(\omega\right)\varrho^*\left(\omega+\Omega\right) - \varrho^*\left(\omega\right)\varrho\left(\omega-\Omega\right)\right]\sin\left(\Omega t\right)$$

which are the *DC*, *In-phase* and *Quadrature-phase* components respectively; the mixer can extract one of the RF terms (I for example), so the resulting error signal is

$$\varepsilon = 2\sqrt{P_{\mathrm{c}}P_{\mathrm{s}}}\Re\left[\varrho\left(\omega\right)\varrho^*\left(\omega+\Omega\right) - \varrho^*\left(\omega\right)\varrho\left(\omega-\Omega\right)\right]$$

The peculiarity of this error signal is that it is a bipolar signal for both the carrier and the sidebands, and it has a steep linear zero-crossing exactly at the resonance; also, the carrier and the sidebands can be recognized easily as they have opposite signs for the zero-crossing.

The Pound-Drever-Hall Technique (5)

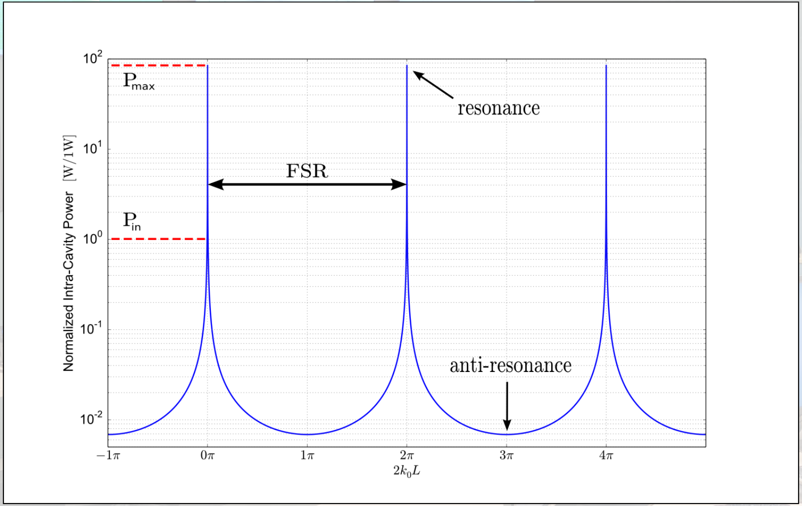


Approximated error signal expression:

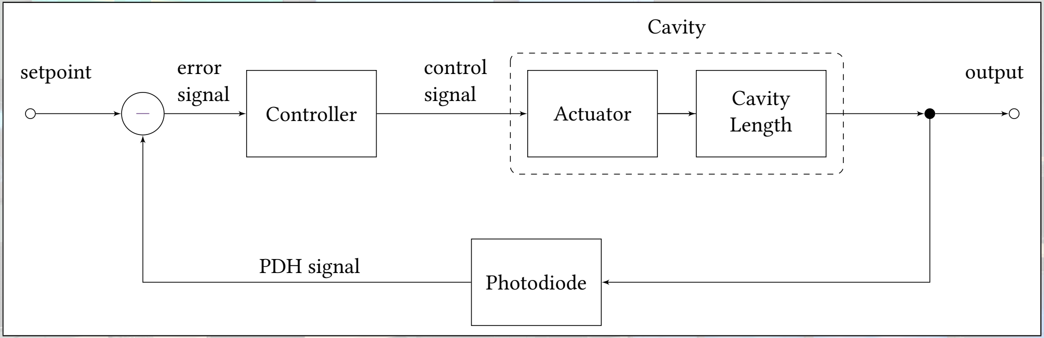
$$\varepsilon \approx -16\sqrt{P_c P_s}\frac{\mathcal{F}}{\lambda_0}\delta L$$

- Linear in the cavity length variation δL
- Dependent on Finesse $\mathcal{F}$ of the cavity
- Narrow linear range in the proximity of the resonance

The Pound-Drever-Hall Technique (6)



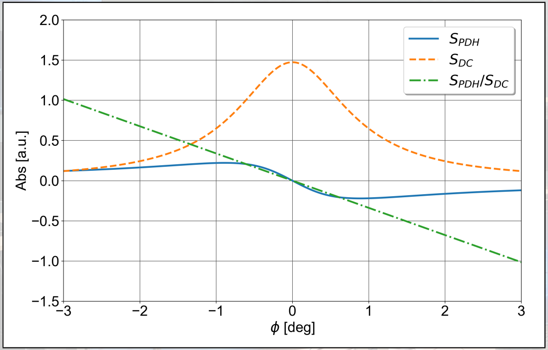
Length Control as a Feedback System



- This is the generic control scheme
- Several different implementations based on it, for different DOFs
- Following are several examples, based on past and future strategies, extracted from the sequential procedures

Example 1: Normalizing PDH Signals

- Normalizing the PDH error signals with the transmitted power increases the linear range
- This comes at the cost of a noisier signal
- In some cases, it is not guaranteed it is sufficient for the PDH lock to succeed

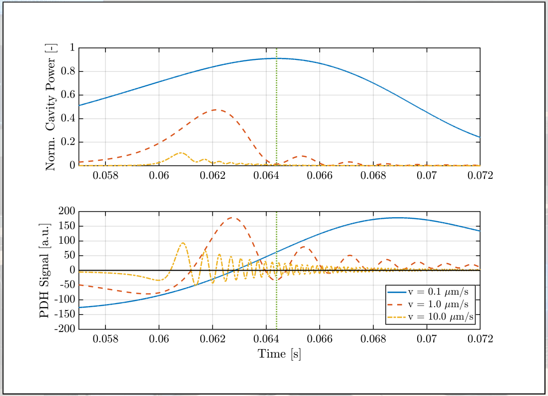


Example 2: *Guided Lock* of a Single Arm Cavity (1)

There are several upper thresholds for the cavity velocity, which is the relative velocity between the two mirrors:

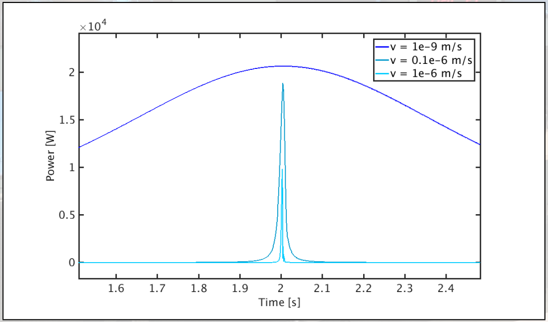
- response time of the feedback loop, which is related to the loop bandwidth
- the maximum force the actuators can do in a finite time
- the finite time needed by the laser field to build up inside the cavity

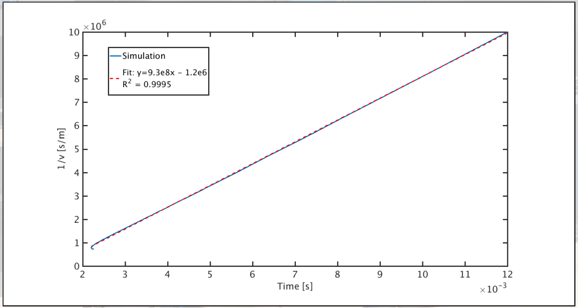
If such speed is above such thresholds the loop cannot be closed as the linear region is too narrow and dynamical ringing effect arise



Example 2: *Guided Lock* of a Single Arm Cavity (2)

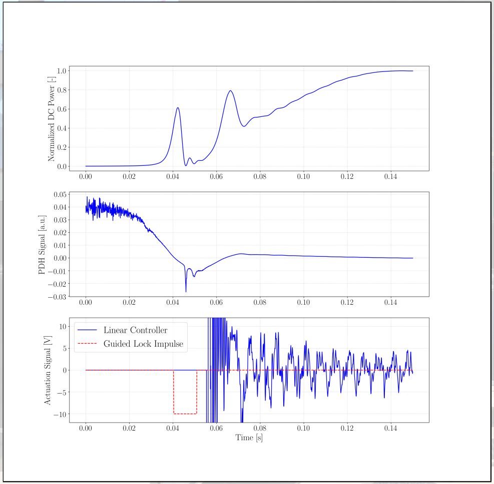
- The peak shape is function of the cavity velocity
- The rising time (already in the 10÷40 % range of the transmitted power) is an estimator





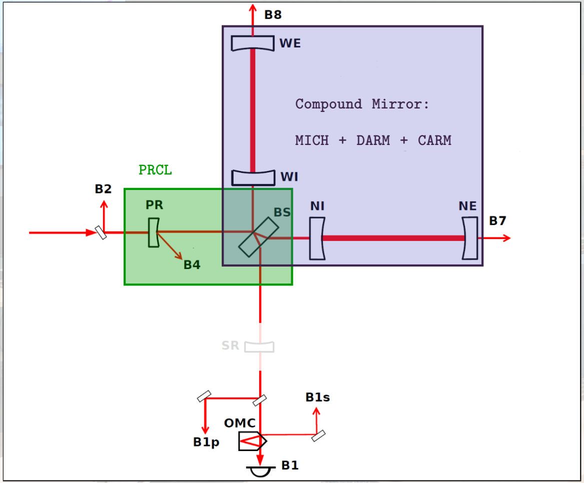
Example 2: *Guided Lock* of a Single Arm Cavity (3)

- The cavity velocity is constantly measured
- If needed, a pulsed actuation at maximum force is sent to slow down the cavity
- Once the cavity is in the linear range, the PDH lock is engaged



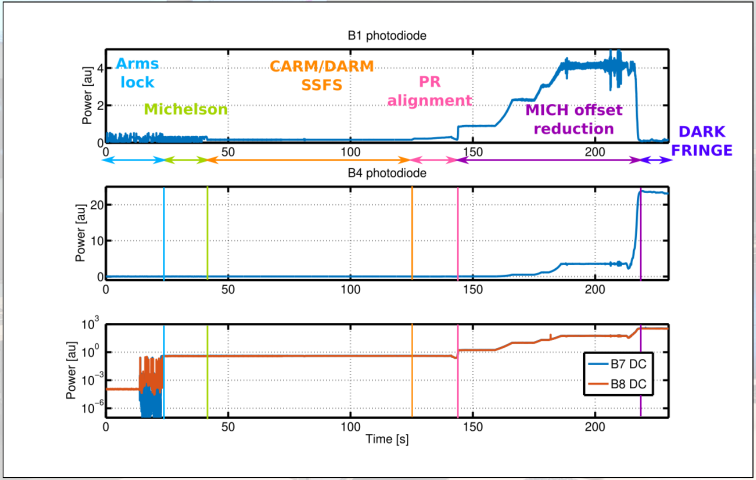
Example 3: *Variable Finesse* Technique (1)

- Used in Advanced Virgo for *O2* and *O3*
- CARM and DARM controlled
- MICH controlled at a brighter fringe (0.7 in the [0, 1] range) with a DC signal
- Interferometer is a single cavity, formed by the PR mirror and a Compound Mirror
- PR is realigned and PRCL closed on the fly



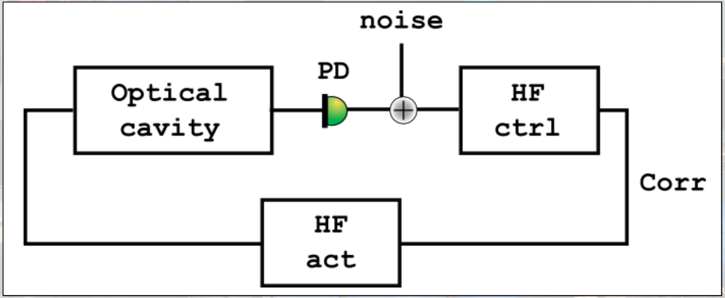
Example 3: *Variable Finesse* Technique (2)

- MICH setpoint is changed and brought towards dark fringe
- Field dynamics changes greatly in the whole interferometer
- Controls change a lot in dark fringe



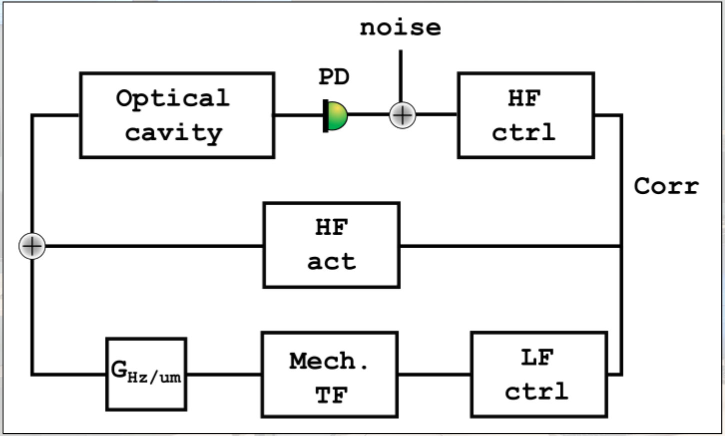
Example 4: Control of the Auxiliary Laser System (1)

- Novelty for *O4*, due to the SR mirror
- Frequency-doubled laser, used for controlling the cavities but away from the main laser resonance
- This uses the original PDH technique: the cavity is free-swinging and the laser frequency is locked to it



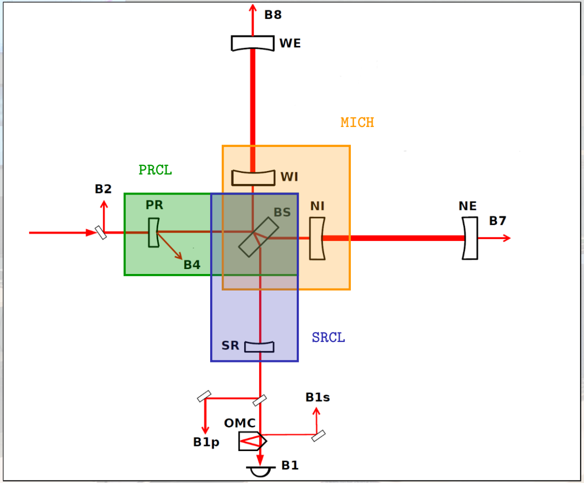
Example 4: Control of the Auxiliary Laser System (2)

- Later, a nested loop is engaged
- The correction signal is used as error signal for a usual PDH loop
- This low-frequency loop actuates on the mirrors instead, reducing the low-frequency residual motion

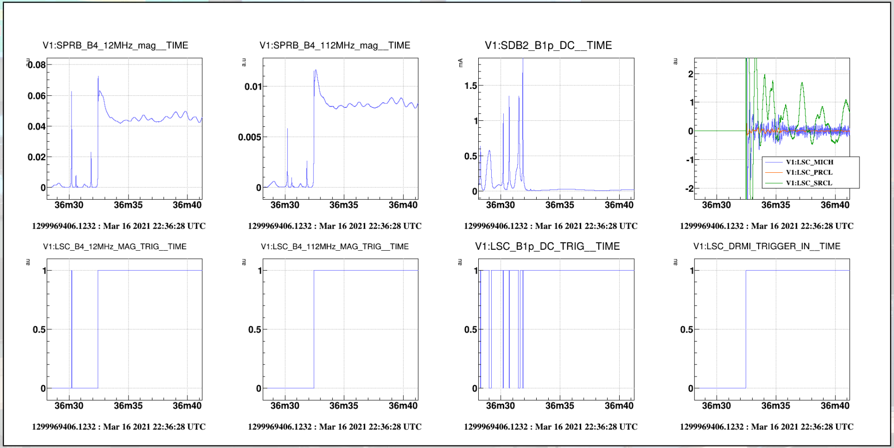


Example 5: *Coincidence Locking* for the DRMI (1)

- Novelty for *O4*, due to the SR mirror
- DRMI: Dual-Recycled Michelson Interferometer
- The three central degrees of freedom (MICH, PRCL and SRCL) are involved, with the End mirrors misaligned *or* the arms locked on the ALS control
- Standard PDH for the lock, but the three DOFs must be engaged at the same time



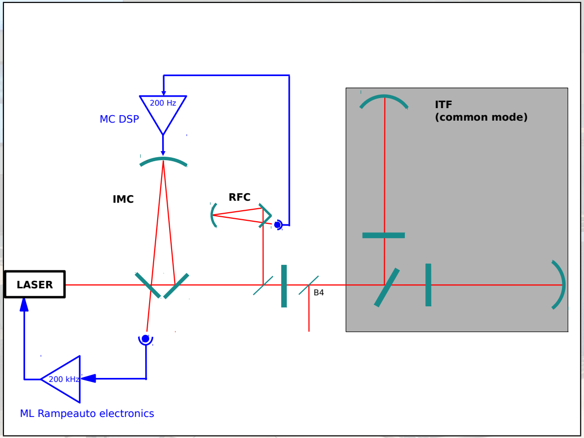
Example 5: *Coincidence Locking* for the DRMI (2)



- Several triggers, based on sidebands resonance and dark fringe condition
- The overall triggers product enables the three loops

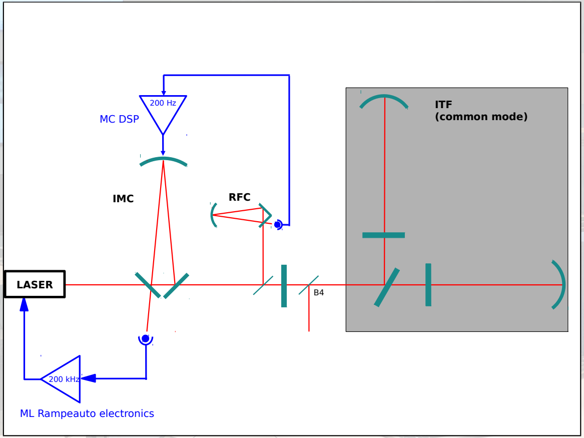
Example 6: The SSFS Loop (1)

- SSFS: Second Stage of Frequency Stabilization:
  - When the injection system is running in stand-alone configuration the laser frequency is locked on the input mode cleaner (IMC) length by using a standard PDH technique in reflection of the IMC cavity (pre-stabilization loop)
  - In this way the laser frequency follows any length variation of the cavity
  - At low frequency these variations can be large since the suspended mirror and bench are free to move



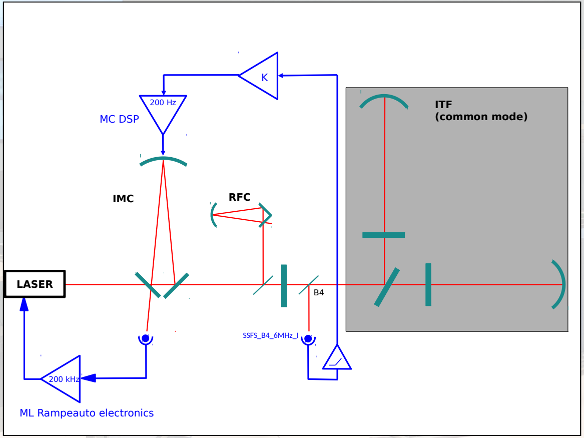
Example 6: The SSFS Loop (2)

- Additional control loop: a rigid reference cavity (RFC) is probed with a pick-off of the beam transmitted by the IMC
- The PDH signal in reflection of this cavity is sensitive to laser frequency variations, which are dominated by the IMC length variations, as an effect of the pre-stabilization loop
- The error signal coming from RFC reflection can be used to control mechanically the IMC end mirror, thus stabilizing the low frequency IMC motion to the rigid RFC reference



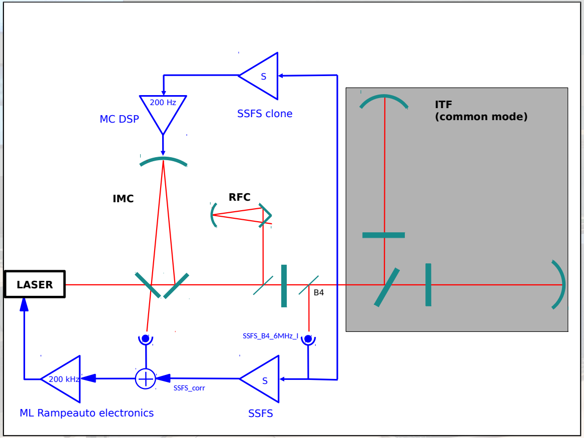
Example 6: The SSFS Loop (3)

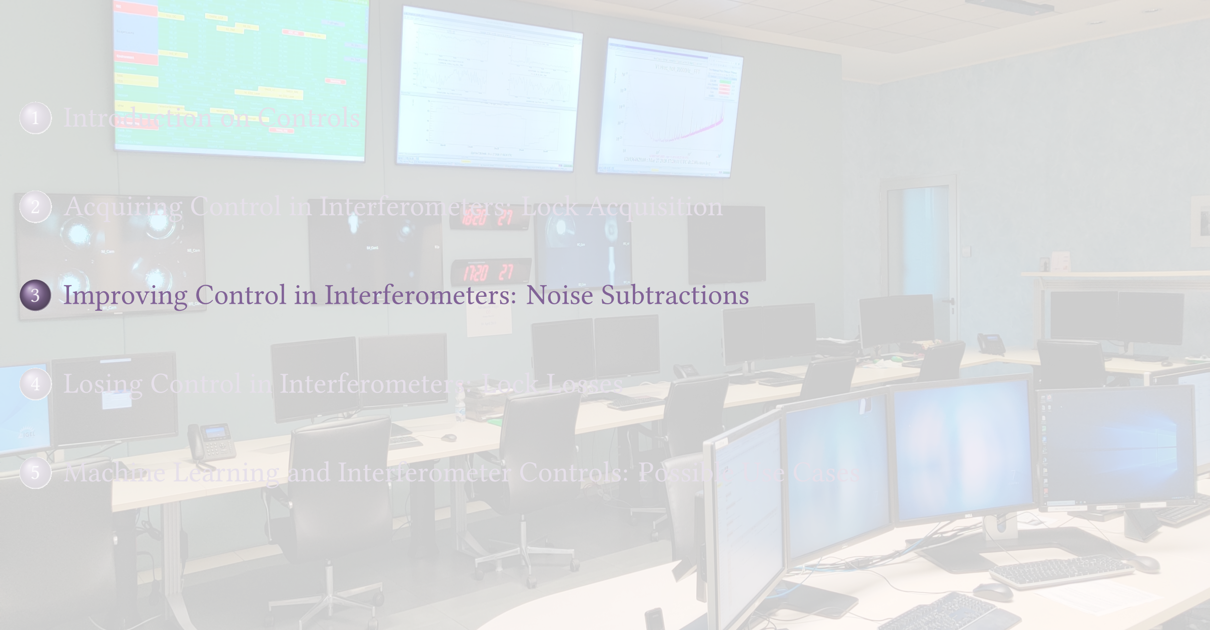
- When the full ITF is locked this stabilization is not enough
- It is necessary to add an additional stage, which uses as reference the arms cavities
- What is really needed for the controls is the relative stability between the laser frequency and the arm length
- The error signal is extracted in reflection of the Power Recycling cavity



Example 6: The SSFS Loop (4)

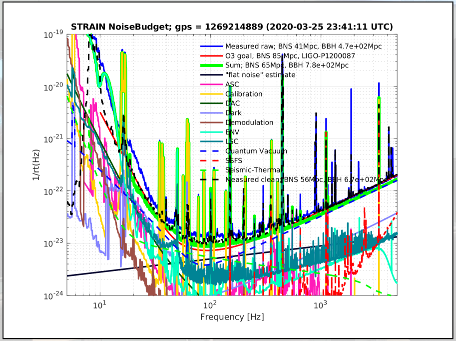
- This correction can't be sent to the laser only, as it'd move the IMC out of resonance
- Electronic summation point: the SSFS correction is summed with proper gain with the PDH signal in reflection of the IMC and this is used as error signal for the pre-stabilization loop
- Another *very slow* loop is added to control very slow cavity length motion, using again the RFC error signal (now out of loop)

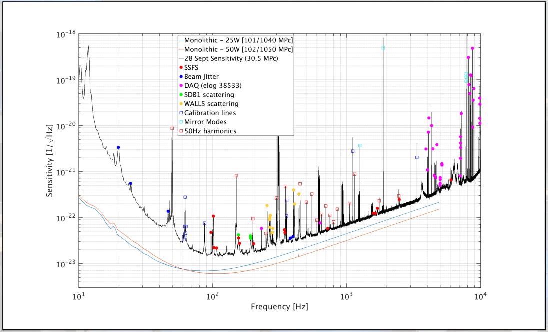




Sensitivity Curve and Noises

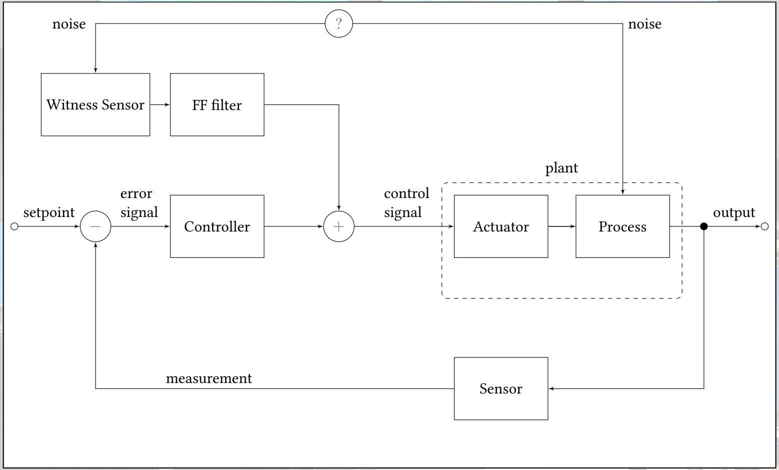
Once the interferometer is fully locked, the Noise Hunting begins:





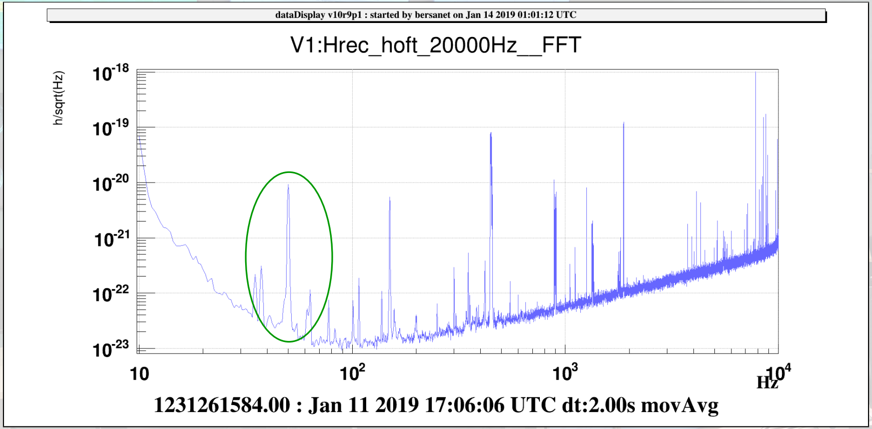
- Some noises are known and evaluated in the Noise Budget, others must be found
- Constant effort to reduce all known noises, and to find the source of the unknown ones

Feed-Forward inside a Feedback Control



- Reduction of an external disturbance from a *in-loop* variable
- The relationship between noise and witness must be well known
- The relationship between noise and actuator must be well known
- A precise model is needed in order to build a performing filter

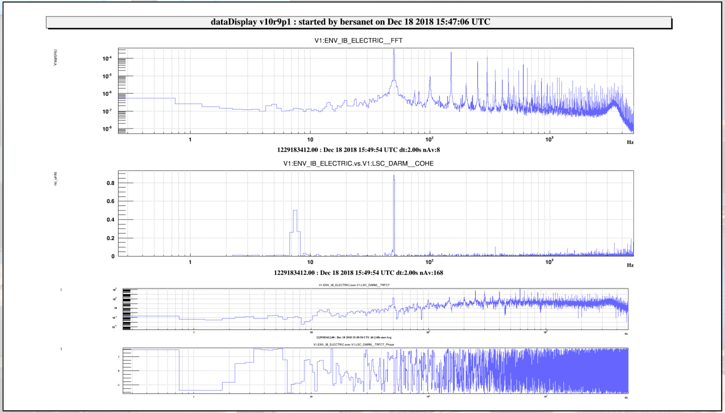
50 Hz Feed-Forward (1): Noise in $h(t)$



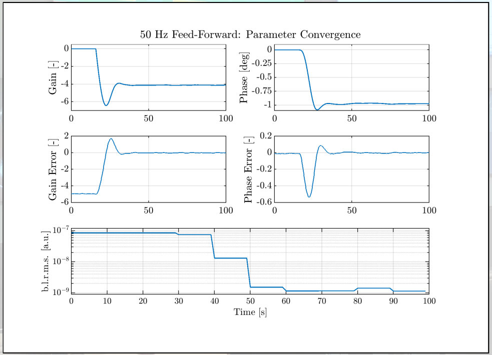
- Known source of noise
- Source is the mains lines
- Source can not be removed
- Effect can be subtracted

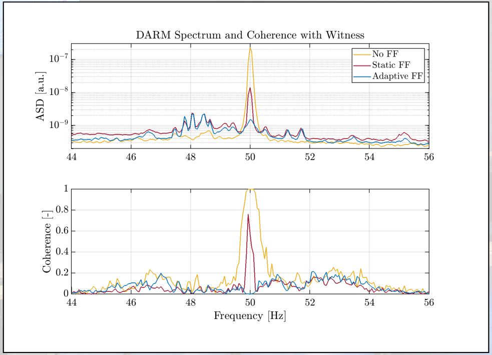
50 Hz Feed-Forward (2): Witness Sensor

- A reliable witness is one of the three phases of a probe of the IPS system
- The first step is the measurement of the TF between the witness and target (DARM)
- The second step is the measurement of the TF between target and actuator used for the subtraction



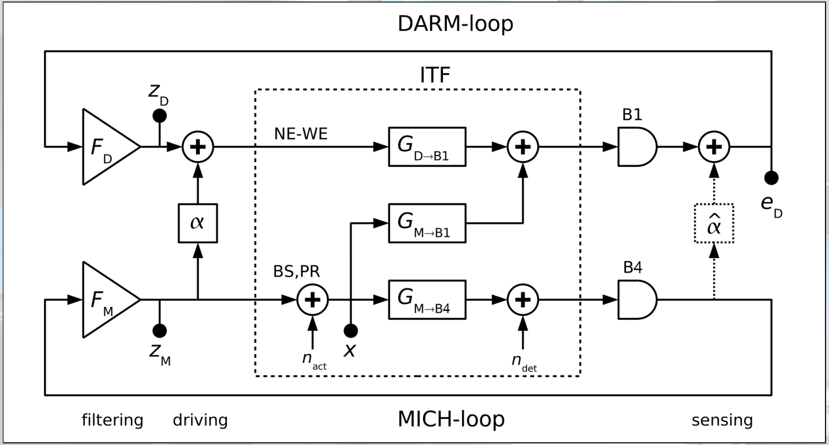
50 Hz Feed-Forward (3): Adaptive Control





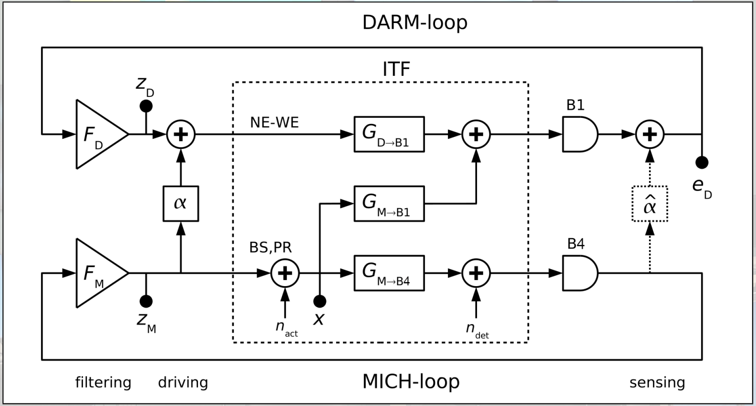
- A resonant gain filter was used
- The coupling was found to be not completely stationary in gain and phase
- Two feedback loops have been implemented to adapt the gain and the phase of the feed-forward subtraction

MICH → DARM Coupling Subtraction (1)



- Coupling between longitudinal DOFs
- Broadband, frequency-dependent behavior
- Most of the coupling is *linear*
- Subtraction is possible

MICH → DARM Coupling Subtraction (2)



- In principle the coupling factor is

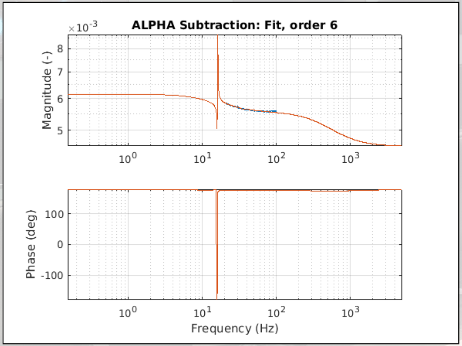
$$\alpha = -\frac{G_{\mathrm{M}\to\mathrm{B1}}}{G_{\mathrm{D}\to\mathrm{B1}}}$$

- But we cannot measure $G_{\mathrm{M}\to\mathrm{B1}}$ directly
- In the real ITF, we have instead:

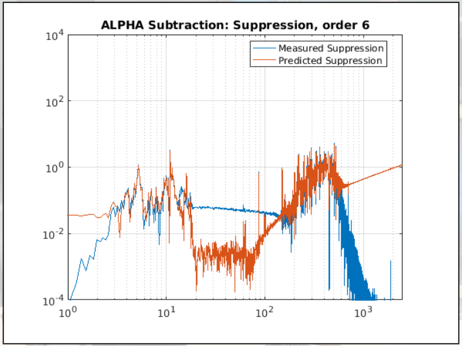
$$\alpha = -\frac{\mathrm{TF}_{\mathrm{M}\to\mathrm{B1}}}{G_{\mathrm{Dcl}} \cdot \mathrm{TF}_{\mathrm{D}\to\mathrm{B1}}} = -\frac{\mathrm{TF}_{\mathrm{M}\to\mathrm{B1}}\left(1 - \mathrm{TF}_{\mathrm{Dpost}\to\mathrm{Dpre}}\right)}{\mathrm{TF}_{\mathrm{D}\to\mathrm{B1}}}$$

MICH → DARM Coupling Subtraction (3)

- Frequency-domain fit to find the feed-forward filter
- Filters of different orders are compared

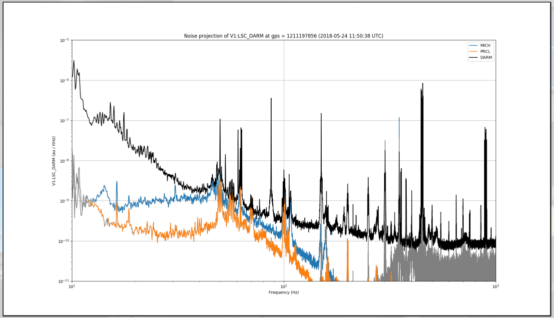


- The predicted new suppression is computed and compared to the current one (if present)

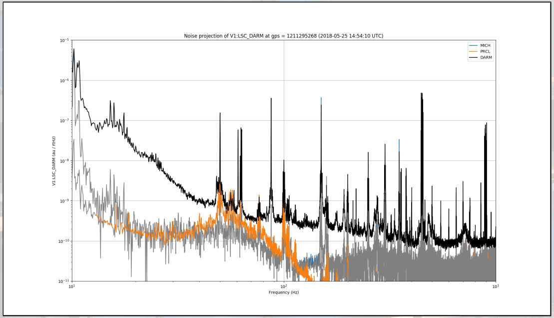


MICH → DARM Coupling Subtraction (4)

- Contribution from MICH is suppressed
- Coherence between DOFs is reduced

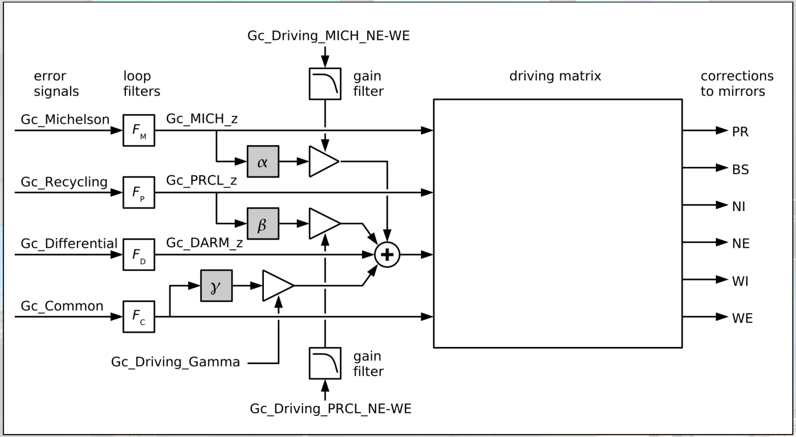


Old feed-forward filter



New feed-forward filter

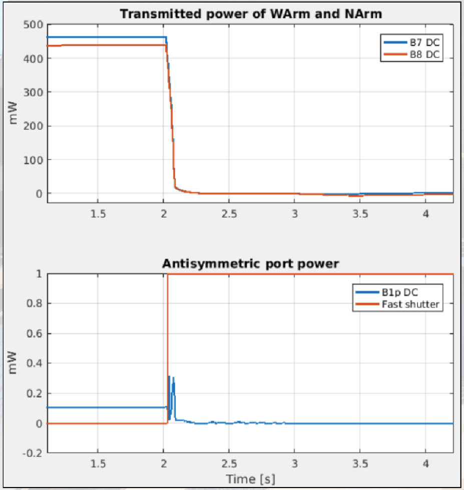
MICH → DARM Coupling Subtraction (5)



- General approach, can be used for any coupling to DARM
- PRCL suppression has been done, in a slightly different way
- The new SRCL DOF will be studied in the same way

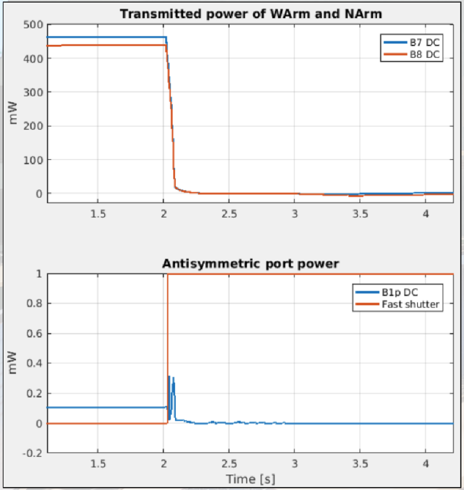
What is a Lock Loss? (1)

- A lock loss is any event which causes the interferometer to lose its working point for operation
- Since the interferometer is a single entity, it can originate in *any* part of it
- For the same reason, there are no *partial* unlocks, or single systems which can be restored: it affects the whole detector, and the Lock Acquisition procedure must be restarted from scratch



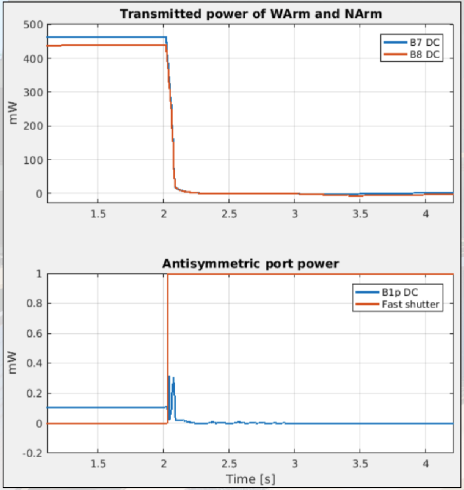
What is a Lock Loss? (2)

- The clearest evidence is the drop of the power transmitted by the arms and the divergence of the power on the detection photodiode (DARM)
- Not all unlocks are equal: signals behavior and their order, timing and other figures of merit may differ from one to the others
- Usually, the same cause of unlock shows a similar behavior of the interferometer
- There are many different causes of unlock, which are studied by commissioners



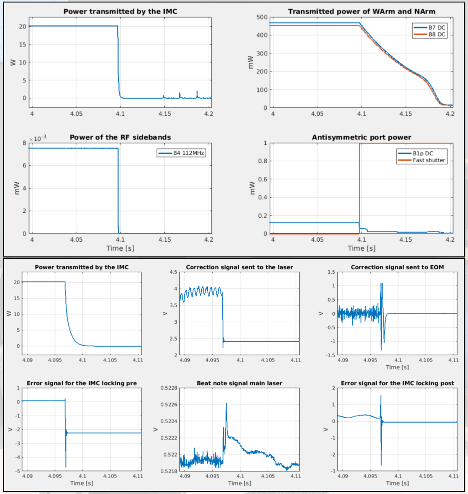
What is a Lock Loss? (3)

- For each typical cause, a set of channels of interest is often found (*a posteriori*), which allows a quicker identification in following occurrences
- This allows some basic statistics and the discovery of major issues in the stability of the detector, which may need an intervention
- A few examples, which show the difference among different types of unlocks (cfr. Casanueva & Tapia: VIR-0264A-21)



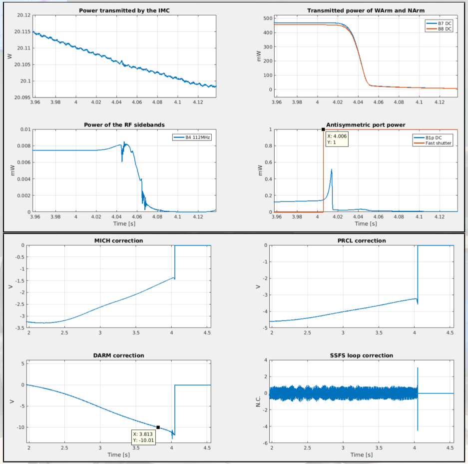
Example 1: Fast Unlock of the Injection System

- Fastest type of unlock
- Easy to spot, always linked to the lock loss also of the Injection system, which cuts the beam from being injected in the interferometer
- The timing is well visible, and signals of the Injection system may show the underlying cause, for example a glitch in the EOM correction



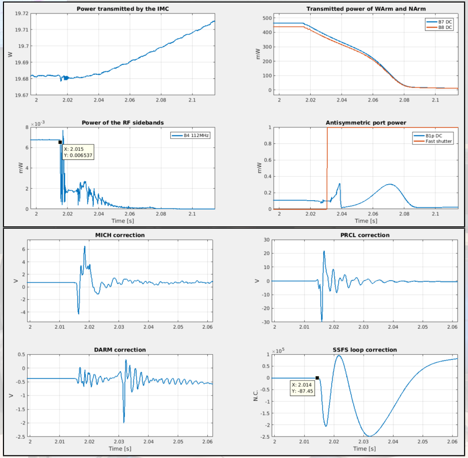
Example 2: B1 Fast Shutter Closing

- The macroscopic cause is the sudden closing of the fast shutter which protects the B1 detection photodiodes
- Since DARM is controlled with them, this causes the unlock of the interferometer
- The cause of the closing itself must be identified, as that is the real cause of unlock: in this case, the saturation of the DARM correction, whose origin is unknown



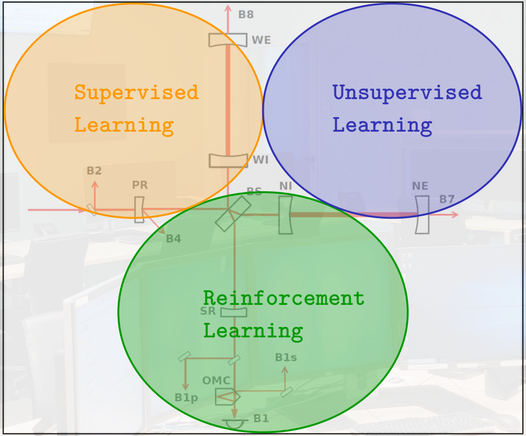
Example 3: Saturation of the Frequency Stabilization Loop

- This is spotted as a sudden drop in the sidebands power
- The origin has been found in the saturation of the SSFS loop for the frequency stabilization
- However, the cause of the saturation has not been identified



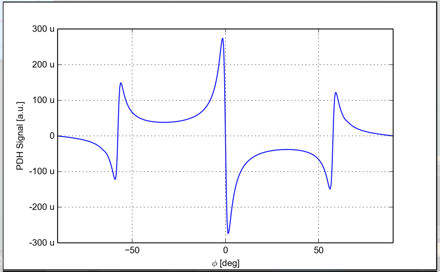
How to apply Machine Learning to Interferometer Controls?

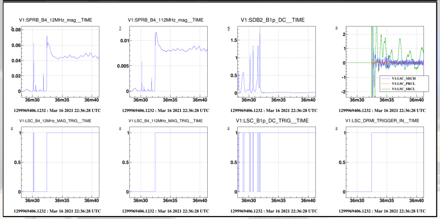
- What has been presented so far is essentially based on classical approaches:
  - Classical control theory
  - Sequential algorithms
  - Transfer functions measurements
  - Human classification and interpretation
- What could be topics of interest for Machine Learning applications?



Machine Learning for Lock Acquisition (1)

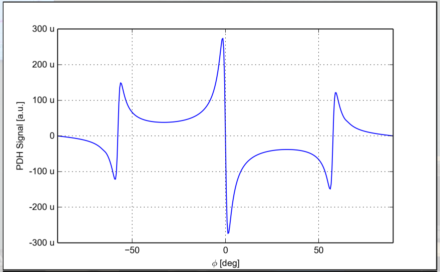
- A big limitation for Lock Acquisition is the narrow linear range of the PDH signals
- This highly reduces the parameter space we can probe with classical controls and forces to sequential locking (*Variable Finesse*) or waiting for favorable conditions (*Coincidence Locking*)
- A proper MIMO approach for the sensing is also made difficult by the non-trivial coupling between DOFs

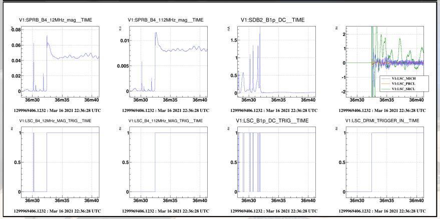




Machine Learning for Lock Acquisition (2)

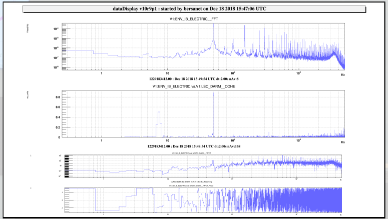
- Could ML algorithms find different probes to read the status of an interferometer?
- Could it be possible to switch to a “cost function” approach?
- Could ML algorithms find a more complete sensing matrix for the interferometer DOFs?

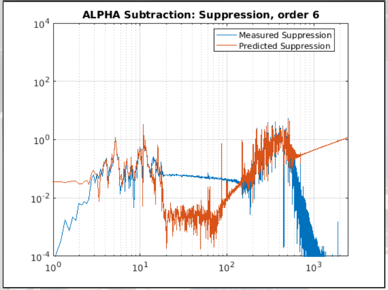




Machine Learning for Noise Subtraction

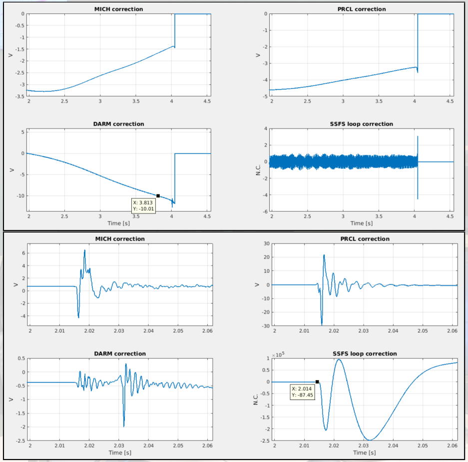
- Could ML help in finding the best witness (or a combination of) for a given disturbance?
- Online adaptation of couplings between DOFs?
- MIMO approach for the reduction of control noises?





Machine Learning for Lock Losses: Analysis and Classification

- Supervised classification of the unlocks seems the more intuitive use case for ML
- Could unsupervised learning detect rare and exotic unlocks?
- Automatic analysis would be a big time saver

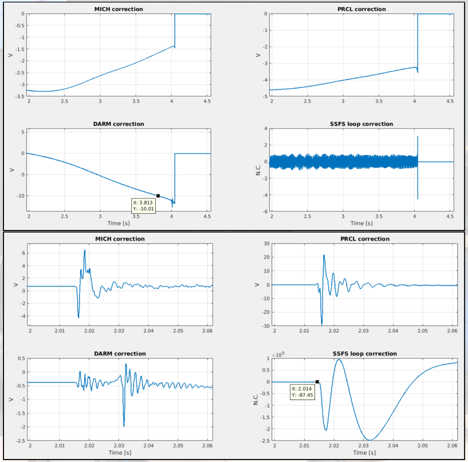


Machine Learning for Lock Losses: Precursors and Prevention

- Could it be possible to *prevent* some unlocks by using ML?

- Unlikely for fast and abrupt events (e.g. fast unlocks), but it could be meaningful for slow drifts or other types of unlocks

- What about detection of earthquakes and automatic switch to more robust controls at the cost of sensitivity, but keeping the lock?



What Comes Next?

- Control of a Laser Interferometer is a challenging topic, which makes extensive use of control techniques, from more standard to more exotic ones
- The current status is that of a mature field, with solid experience in classical controls
- For the current upgrades and the future generation, the use of more modern control theory and Machine Learning could help both Commissioning and Detector Characterization
- A few areas of interest for Machine Learning applications can be already considered

Thank You