

# Suspension Control

## AdVirgo+ Experience

V. Boschi

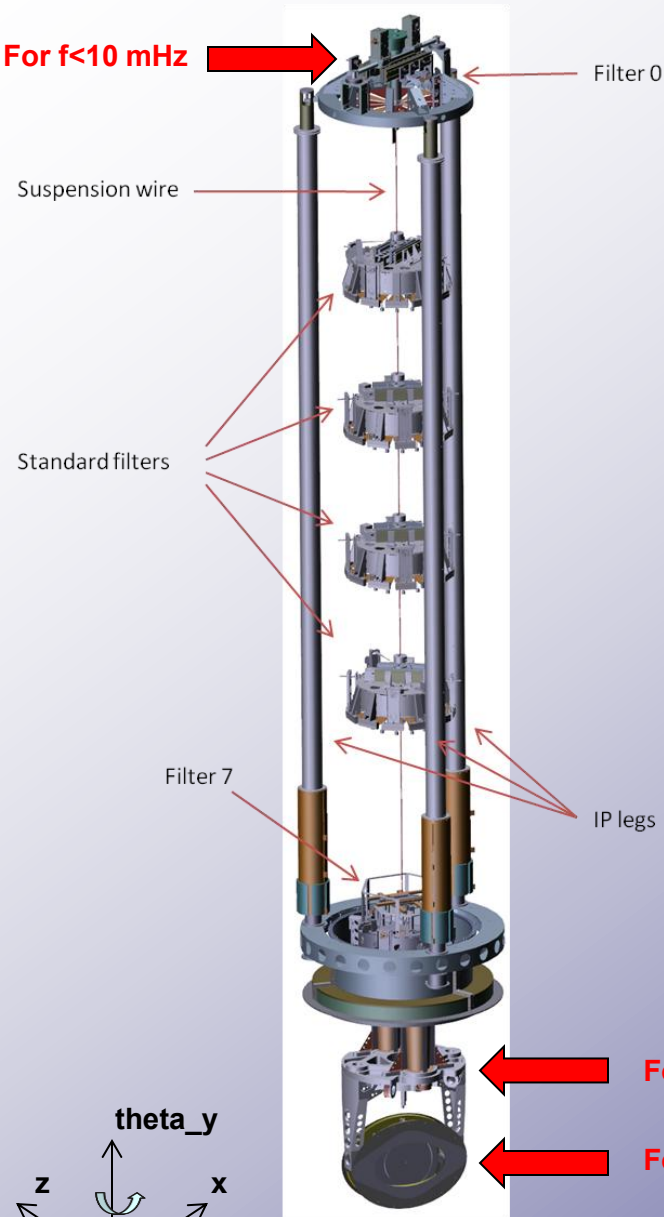
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# Introduction

## Control system setup



The control system has been designed using a hierarchical strategy regulated by the dynamic range of the actuators.

- 23 Coil Magnet Actuators in 3 points (**actuation stages**) of the SA:

- **Filter 0:**

Large displacements (hundreds of microns) for  $f < 10$  mHz.

- **Filter 7 + Marionette:**

Small payload displacements (1 micron) in the  $10 \text{ mHz} < f < 1 \text{ Hz}$  band.

- **Filter 7 + Mirror:**

Small residual mirror displacements (a few nm), for  $f > 1 \text{ Hz}$ .

- >20 Local Sensors

- Accelerometers
- 4 Displacements Sensors (LVDTs) on Filter 0
- 6 Displacements Sensors on Filter 0
- Optical Readout of Marionette and Mirror Position

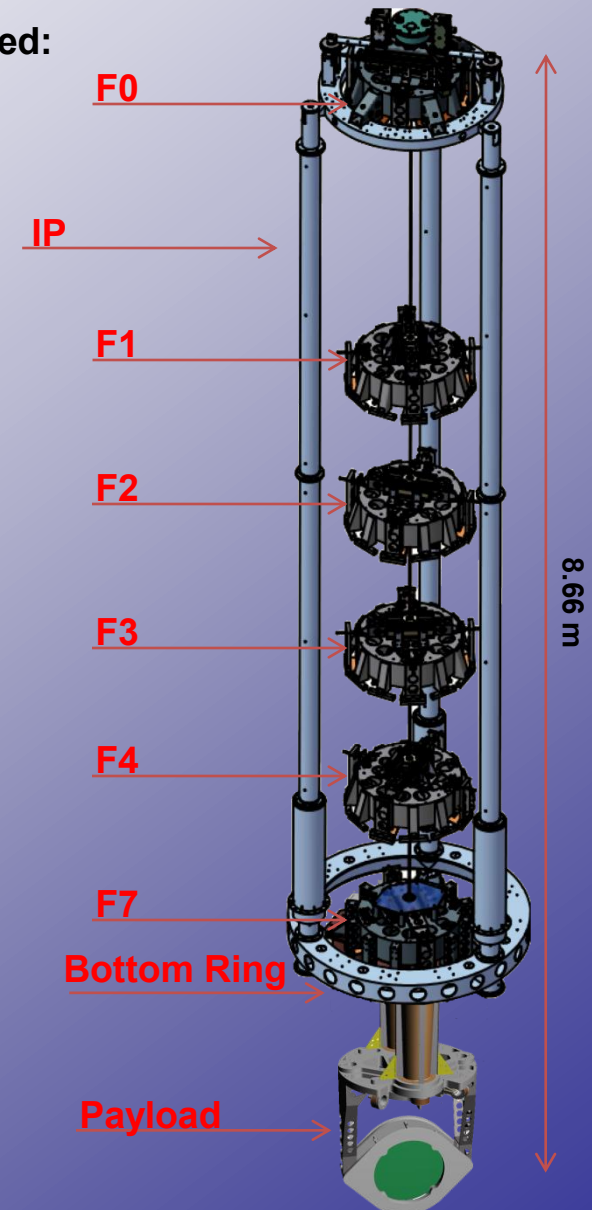
- Digital Control system based on high-performance multicore DSPs.

# Introduction

## Control system setup

On long superattenuators (BS, NI, NE, WI, WE, PR, SR) are installed:

- **18 LVDTs** of 3 different types
  - 9 Vertical LVDTs (F0 – F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
  - 6 F7 LVDTs
- **5 Accelerometers** of 2 different types installed on F0:
  - 3 Horizontal Accs
  - 2 Vertical Accs
- **23 Coils** of 4 different types
  - 5 F0 Coils
  - 6 F7 Coils
  - 8 Marionette coils
  - 4 Mirror coils
- **3 Piezos** on bottom ring (**Not uset yet**)
- **21 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 6 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors



# Introduction

## Control system setup

On IB superattenuator are installed:

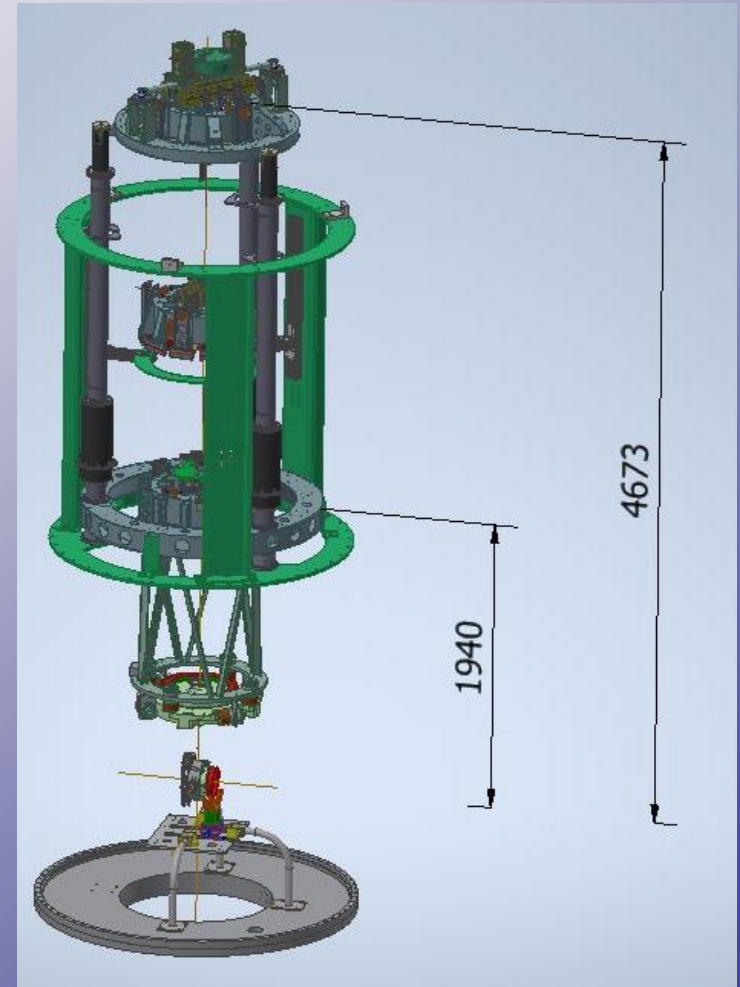
- **9 LVDTs** of 2 different types
  - 6 Vertical LVDTs (F0, F4, F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
- **5 Accelerometers** of 2 different types installed on F0:
  - 3 Horizontal Accs
  - 2 Vertical Accs
- **13 Coils** of 2 different types
  - 5 F0 Coils
  - 8 Marionette coils
- **3 Piezos** on bottom ring (**Not used yet**)
- **18 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 3 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors

# Introduction

## Control system setup

On MC superattenuator are installed:

- **9 LVDTs** of 2 different types
  - 6 Vertical LVDTs (F0, F4, F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
- **5 Accelerometers** of 2 different types installed on F0:
  - 3 Horizontal Accs
  - 2 Vertical Accs
- **17 Coils** of 3 different types
  - 5 F0 Coils
  - 8 Marionette Coils
  - 4 Mirror Coils
- **3 Piezos** on bottom ring (**Not used yet**)
- **19 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 4 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors



# Introduction

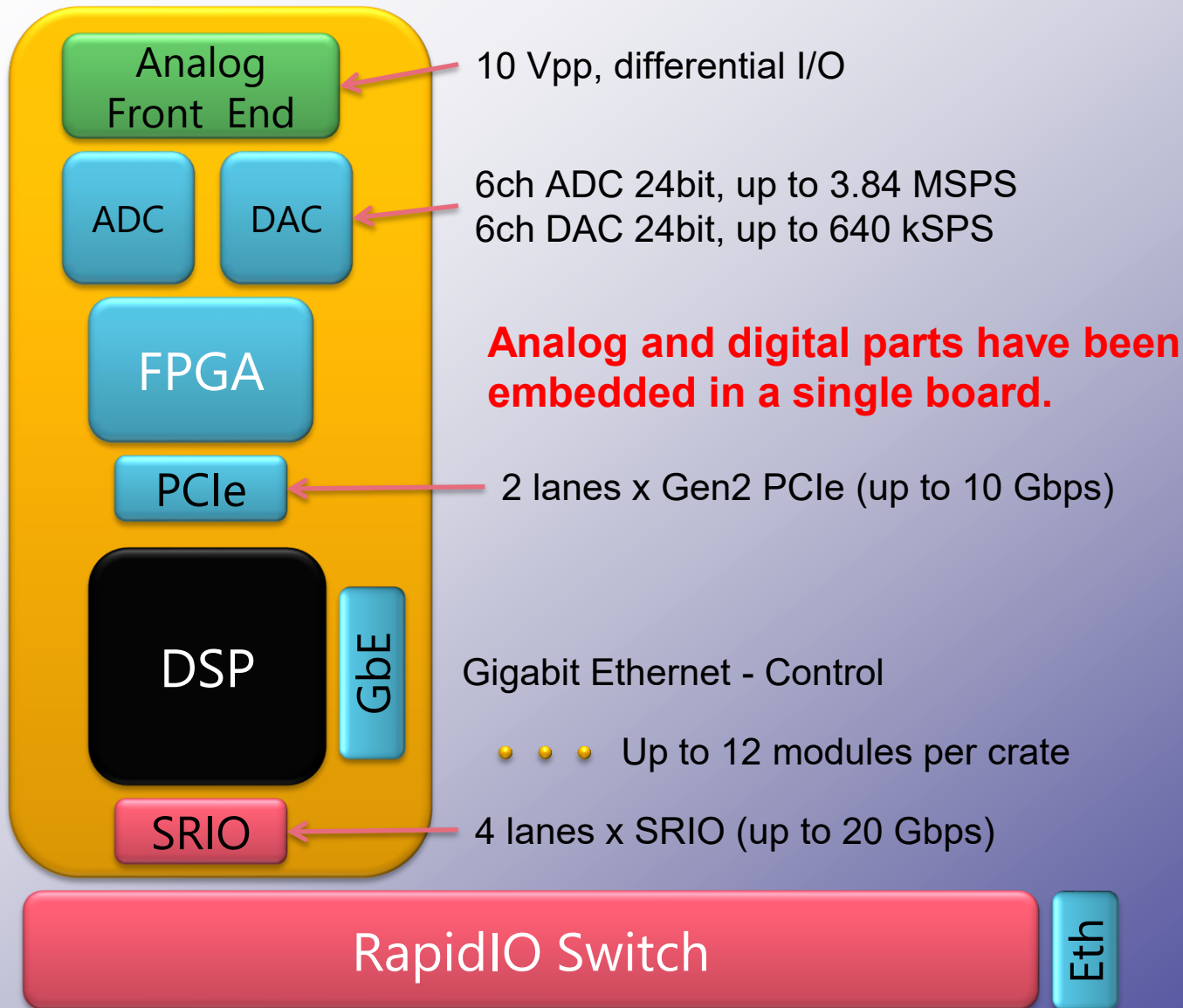
## Control system setup

On detection (SDB1) superattenuator (OB) are installed:

- **9 LVDTs** of 3 different types
  - 6 Vertical LVDTs (F0, F4, F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
- **5 Accelerometers** of 2 different types installed on F0:
  - 3 Horizontal Accs
  - 2 Vertical Accs
- **5 F0 Coils**
- **3 Piezos** on bottom ring (**Not used yet**)
- **18 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 3 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors

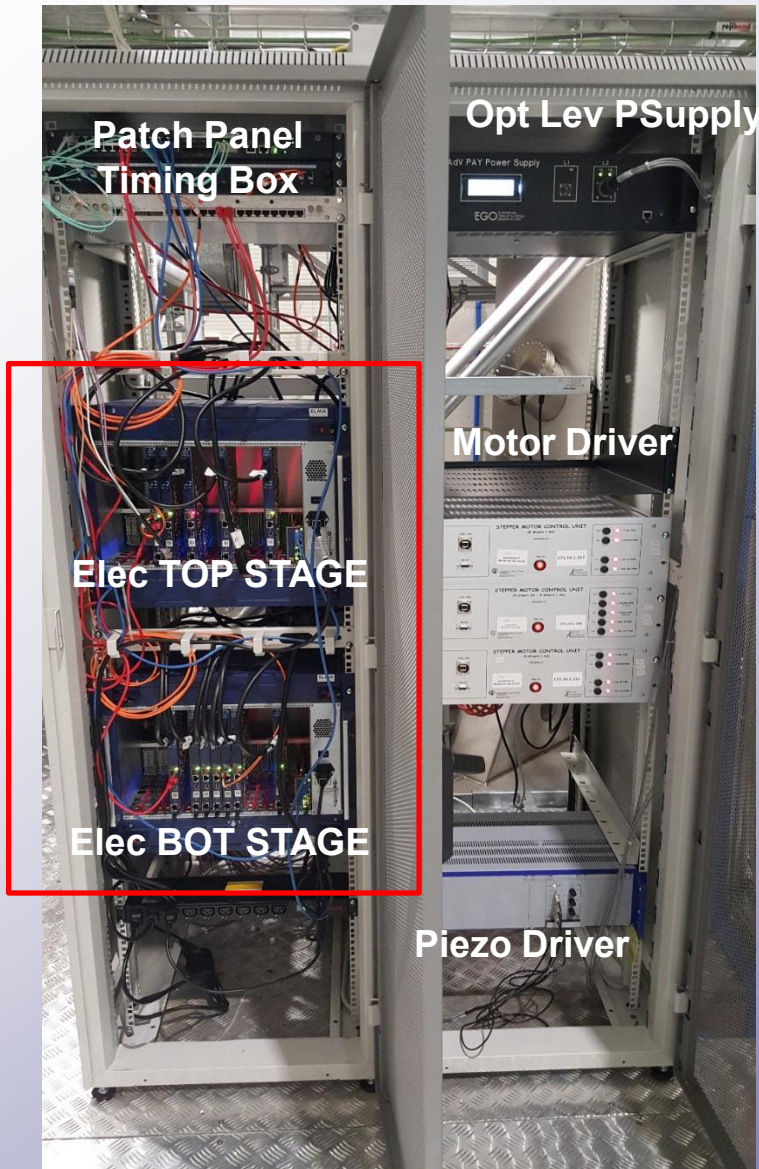
# Introduction

## Control system setup

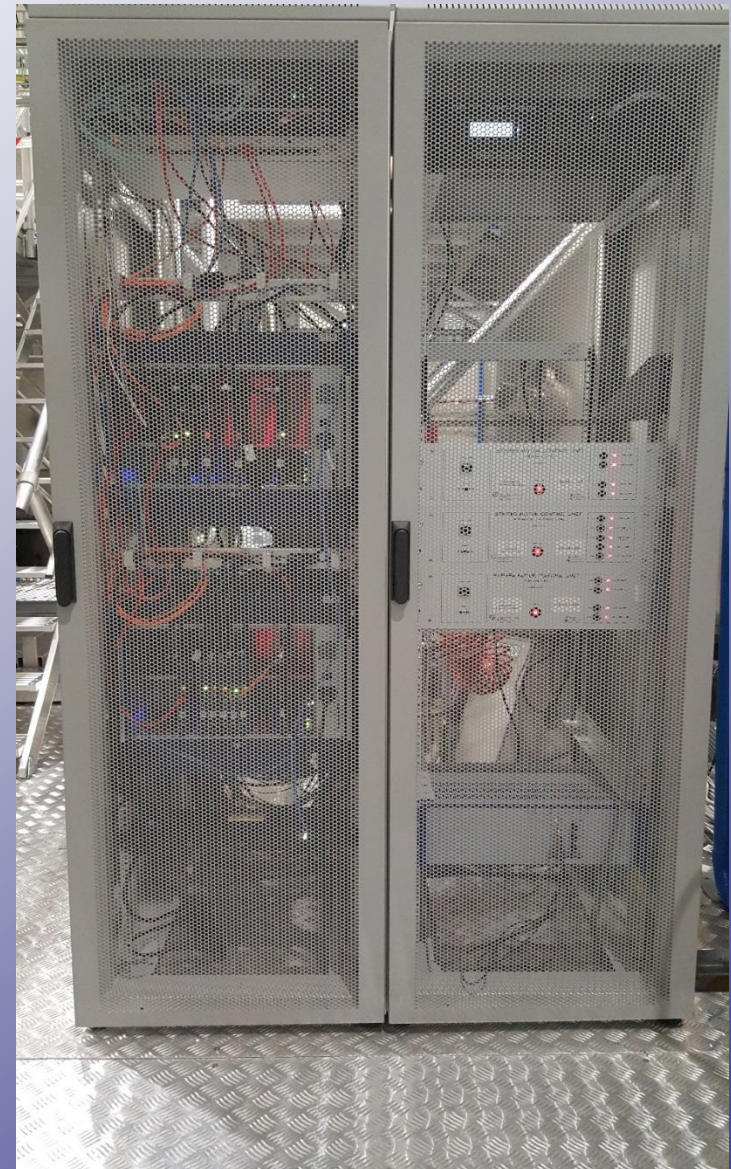


# Introduction

## Control system setup



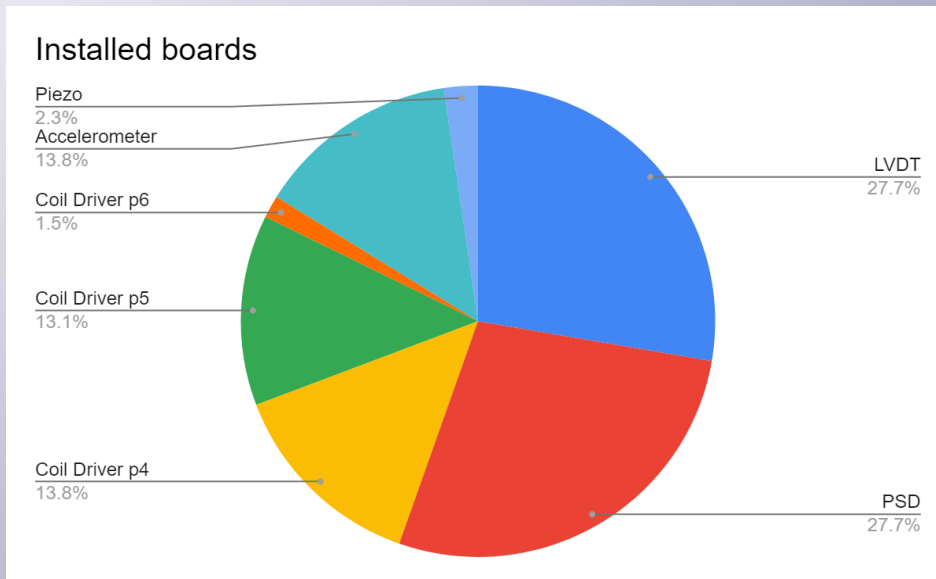
NI Tower



# Introduction

## Control system setup

- There is a total of 130 DSP boards in SAT, PAY, INJ of 7 alternative configurations depending on their use:
  - LVDT**: digital demodulation of horizontal and vertical LVDTs of F0 and F7.
  - Accelerometer**: LVDT digital demodulation and control of the sensing element of both horizontal and vertical F0 accelerometers.
  - PSD**: signal acquisition of mirror (PSDf, PSDi) and marionette (PSDm, PSDt) optical lever PSDs.
  - Coil Driver p4**: the board is equipped with TI OPA544 operational amplifier and is used for F0 and F7 actuation. The opamp is capable of erogating a peak current of 310 mA.
  - Coil Driver p5**: the board is equipped with AD8397 operational amplifier and is used for mirror and marionette high power actuation. The opamp is capable of erogating a peak current of 2 A. This board type has been produced in limited quantities (20 samples).
  - Coil Driver p6**: the board is equipped with analog shaping filters, TI OPA1612 operational amplifiers and it is used for NE and WE low noise mirror actuation. The opamp is capable of erogating a peak current of 40 mA.
  - Piezo**: driving of bottom ring piezoelectric actuators.

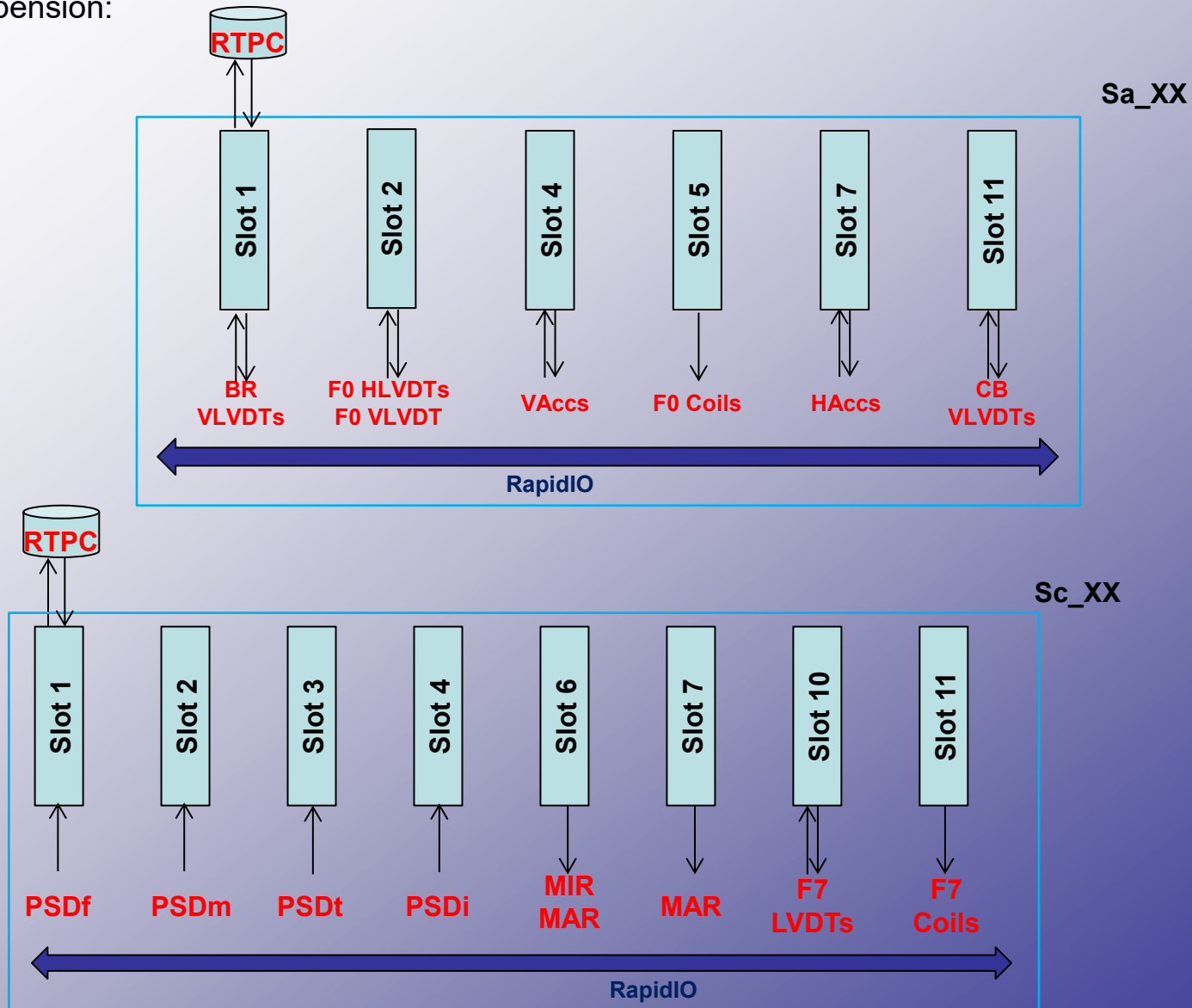


Electronic board name	Installed Boards	% (P <sub>i</sub> )
LVDT	36	28
PSD	36	28
Coil Driver p4	18	14
Coil Driver p5	17	13
Coil Driver p6	2	2
Accelerometer	18	14
Piezo	3	2
Total	130	

# Introduction

## Control system setup

- A total of 14 boards, each one equipped with an 8-core TMS320C6678 DSP, are connected to each long suspension:



# Introduction

## Control system setup

### SA control is an extremely complex system:

- **130** DSP boards are installed on BPC, BS, IB, MC, PR, NI, NE, WI, WE, SR, OB
- **185** control code files are running at the same time on the DSP cores at 10 kHz (IP, F7, LC controls), 40 kHz (Global signals oversampling) and 320 kHz (Digital demodulation of sensors)
- All the DSP software (code, generated assembler and binaries) is archived in an SVN repo that can be browsed:  
[https://svn.ego-gw.it/svn/satsw/DSPCode\\_Adv/](https://svn.ego-gw.it/svn/satsw/DSPCode_Adv/)

O2 SOFTWARE MAP

SA	BOARD IP	CONNECTED DEVICES	SOFTWARE RUNNING (Core4, 10 kHz)	SOFTWARE RUNNING (Core1, 320 kHz)
BPC	172.16.2.104	PSD	/virgoDev/Sa/DSPCode_Adv/BPC/BPC_PSD	
BPC	172.16.2.141	PIEZO	/virgoDev/Sa/DSPCode_Adv/BPC/BPC_CD	
Sa_BS	172.16.2.62	BR LVDTs	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_MASTER	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_BR_LVDT_Demod
Sa_BS	172.16.2.53	F0 LVDTs	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_LVDT_HS_SRIO	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_LVDT_HG2
Sa_BS	172.16.2.32	F0 VAccs	/virgoDev/Sa/DSPCode_Adv/BS/Accs/BS_vAcc_LQG	/virgoDev/Sa/DSPCode_Adv/BS/Accs/BS_vAcc_Demod
Sa_BS	172.16.2.33	F0 Coils	/virgoDev/Sa/DSPCode_Adv/BS/InertialDamping/BS_ID_Diag	
Sa_BS	172.16.2.133	F0 HAccs	/virgoDev/Sa/DSPCode_Adv/BS/Accs/BS_Acc_LQG	/virgoDev/Sa/DSPCode_Adv/BS/Accs/BS_Acc_Demod
Sa_BS	172.16.2.52	F1-F7 VLVDTs	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_VLVDT_SRIO	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_VLVDT
Sc_BS	172.16.2.80	PSD	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_PSDf	
Sc_BS	172.16.2.108	PSD	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_PSDm	
Sc_BS	172.16.2.110	PSD	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_PSDt	
Sc_BS	172.16.2.84	PSD	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_PSDi	
Sc_BS	172.16.2.181	MIR, MAR Coils	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_Mir	
Sc_BS	172.16.2.179	MAR Coils	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_Mar	
Sc_BS	172.16.2.139	F7 LVDT	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_F7_LVDT	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_F7_LVDT_Demod
Sc_BS	172.16.2.120	F7 Coils	/virgoDev/Sa/DSPCode_Adv/BS/F7/BS_F7_CD	
Sa_IB	172.16.2.28	BR LVDTs	/virgoDev/Sa/DSPCode_Adv/IB/LVDT/IB_MASTER	/virgoDev/Sa/DSPCode_Adv/IB/LVDT/IB_BR_LVDT_Demod
Sa_IB	172.16.2.130	F0, F4, F7 LVDTs	/virgoDev/Sa/DSPCode_Adv/IB/LVDT/IB_LVDT	/virgoDev/Sa/DSPCode_Adv/IB/LVDT/IB_LVDT_Demod
Sa_IB	172.16.2.9	F0 VAccs	/virgoDev/Sa/DSPCode_Adv/IB/Accs/IB_vAcc_LQG	/virgoDev/Sa/DSPCode_Adv/IB/Accs/IB_vAcc_Demod
Sa_IB	172.16.2.121	F0 Coils	/virgoDev/Sa/DSPCode_Adv/IB/InertialDamping/IB_ID_Diag	
Sa_IB	172.16.2.23	F0 HAccs	/virgoDev/Sa/DSPCode_Adv/IB/Accs/IB_Acc_LQG	/virgoDev/Sa/DSPCode_Adv/IB/Accs/IB_Acc_Demod
Sc_IB	172.16.2.118	PSD	/virgoDev/Sa/DSPCode_Adv/IB/LC/IB_PSDf	
Sc_IB	172.16.2.86	PSD	/virgoDev/Sa/DSPCode_Adv/IB/LC/IB_PSDi	
Sc_IB	172.16.2.107	PSD	/virgoDev/Sa/DSPCode_Adv/IB/LC/IB_PSDt	
Sc_IB	172.16.2.173	MAR Coils	/virgoDev/Sa/DSPCode_Adv/IB/LC/IB_Mar1	
Sc_IB	172.16.2.174	MAR Coils	/virgoDev/Sa/DSPCode_Adv/IB/LC/IB_Mar2	
Sa_MC	172.16.2.128	BR LVDTs	/virgoDev/Sa/DSPCode_Adv/MC/LVDT/MC_MASTER	/virgoDev/Sa/DSPCode_Adv/MC/LVDT/MC_BR_LVDT_Demod
Sa_MC	172.16.2.51	F0, F4, F7 LVDTs	/virgoDev/Sa/DSPCode_Adv/MC/LVDT/MC_LVDT	/virgoDev/Sa/DSPCode_Adv/MC/LVDT/MC_LVDT_Demod
Sa_MC	172.16.2.158	F0 VAccs	/virgoDev/Sa/DSPCode_Adv/MC/Accs/MC_vAcc_LQG	/virgoDev/Sa/DSPCode_Adv/MC/Accs/MC_vAcc_Demod
Sa_MC	172.16.2.103	F0 Coils	/virgoDev/Sa/DSPCode_Adv/MC/InertialDamping/MC_ID_Diag	
Sa_MC	172.16.2.14	F0 HAccs	/virgoDev/Sa/DSPCode_Adv/MC/Accs/MC_Acc_LQG	/virgoDev/Sa/DSPCode_Adv/MC/Accs/MC_Acc_Demod
Sa_MC	172.16.2.150	PIEZO	/virgoDev/Sa/DSPCode_Adv/MC/Tilt/Piezo_Test	
Sc_MC	172.16.2.101	PSD	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_PSDf	
Sc_MC	172.16.2.168	PSD	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_PSDi	
Sc_MC	172.16.2.88	PSD	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_PSDTf	
Sc_MC	172.16.2.109	PSD	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_PSDTi	
Sc_MC	172.16.2.171	MAR Coils	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_Mar1	
Sc_MC	172.16.2.172	MAR Coils	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_Mar2	
Sc_MC	172.16.2.176	MIR Coils	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_Mir	
Sa_NE	172.16.2.37	BR LVDTs	/virgoDev/Sa/DSPCode_Adv/NE/LVDT/NE_MASTER	/virgoDev/Sa/DSPCode_Adv/NE/LVDT/NE_BR_LVDT_Demod
Sa_NE	172.16.2.40	F0 LVDTs	/virgoDev/Sa/DSPCode_Adv/NE/LVDT/NE_LVDT	/virgoDev/Sa/DSPCode_Adv/NE/LVDT/NE_LVDT_Demod

# Sensors

## LVDTs

- There are 18 LVDTs installed on long tower suspensions of 3 different types
  - 9 Vertical LVDTs (F0 – F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
  - 6 F7 LVDTs
- Each sensors have been characterized and calibrated
- All the LVDTs are operated using a digital demodulation scheme at 320 kHz sampling frequency:

Level: Top Virgo Inertial damping on [ 172.16.2.14 ] Page 1

Hardware implementation BS\_VLVD00\_00.hrd

Ramp Time [100.00] Downsampling Factor [1]  
Sampling Frequency [320000.00] Oversampling Factor [1]

Input	Output	Filename	GUARD	Gain	Gname	@Frequency	When
ADC1	sc1	NULL	no	1			
ADC2	sc2	NULL	no	1			
ADC3	sc3	NULL	no	1			
ADC4	sc4	NULL	no	1			
ADC5	sc7	NULL	no	1			
SIG_GEN	pr1	sine1	no	1			
SIG_GEN	pr2	sine2	no	1			
SIG_GEN	pr3	sine3	no	1			
SIG_GEN	pr4	sine4	no	1			
SIG_GEN	pr7	sine7	no	1			
ADD	phase1_1		no	-83.44			
ADD	phase1_2		no	6.56			
ADD	phase2_1		no	-85.32			
ADD	phase2_2		no	4.68			
ADD	phase3_1		no	-83.76			
ADD	phase3_2		no	6.24			
ADD	phase4_1		no	-82.06			
ADD	phase4_2		no	7.94			
ADD	phase7_1		no	-75.95			
ADD	phase7_2		no	14.05			
SIG_GEN	mod_sin1	mod_sin1	no	1			
SIG_GEN	mod_cos1	mod_cos1	no	1			
SIG_GEN	mod_sin2	mod_sin2	no	1			
SIG_GEN	mod_cos2	mod_cos2	no	1			
SIG_GEN	mod_sin3	mod_sin3	no	1			
SIG_GEN	mod_cos3	mod_cos3	no	1			
SIG_GEN	mod_sin4	mod_sin4	no	1			
SIG_GEN	mod_cos4	mod_cos4	no	1			
SIG_GEN	mod_sin7	mod_sin7	no	1			
SIG_GEN	mod_cos7	mod_cos7	no	1			
pr1	DAC1	NULL	no	5			
pr2	DAC2	NULL	no	5			
pr3	DAC3	NULL	no	5			
pr4	DAC4	NULL	no	5			
pr7	DAC5	NULL	no	5			
MIX	mm1_sin	mix_sin1	no	1.0			

Secondary signals  
Modulation signals  
Demodulation phases  
Demodulation signals

Level: Top Virgo Inertial damping on [ 172.16.2.14 ] Page 2

Hardware implementation BS\_VLVD00\_00.hrd

Ramp Time [100.00] Downsampling Factor [1]  
Sampling Frequency [320000.00] Oversampling Factor [1]

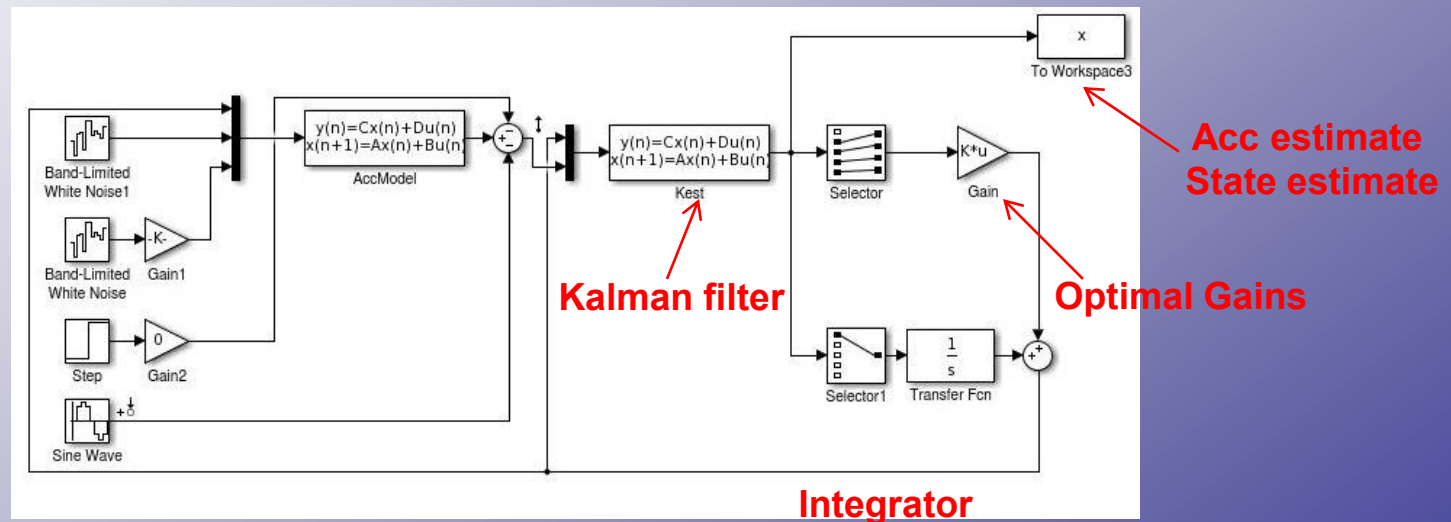
Input	Output	Filename	GUARD	Gain	Gname	@Frequency	When
MIX	mm1_cos	mix_cos1	no	1.0			
MIX	mm2_sin	mix_sin2	no	1.0			
MIX	mm2_cos	mix_cos2	no	1.0			
MIX	mm3_sin	mix_sin3	no	1.0			
MIX	mm3_cos	mix_cos3	no	1.0			
MIX	mm4_sin	mix_sin4	no	1.0			
MIX	mm4_cos	mix_cos4	no	1.0			
MIX	mm7_sin	mix_sin7	no	1.0			
MIX	mm7_cos	mix_cos7	no	1.0			
mm1_sin	lvd11	lpflt	no	600		0.0	after
mm1_cos	lvd11_cos	lpflt	no	600		0.0	after
mm2_sin	lvd12	lpflt	no	600		0.0	after
mm2_cos	lvd12_cos	lpflt	no	600		0.0	after
mm3_sin	lvd13	lpflt	no	600		0.0	after
mm3_cos	lvd13_cos	lpflt	no	600		0.0	after
mm4_sin	lvd14	lpflt	no	600		0.0	after
mm4_cos	lvd14_cos	lpflt	no	600		0.0	after
mm7_sin	lvd17	lpflt	no	600		0.0	after
mm7_cos	lvd17_cos	lpflt	no	600		0.0	after
lvd11	PROBE	F1_vLVD1		1.0			
lvd12	PROBE	F2_vLVD1		1.0			
lvd13	PROBE	F3_vLVD1		1.0			
lvd14	PROBE	F4_vLVD1		1.0			
lvd17	PROBE	F7_vLVD1		1.0			

Low pass output filter  
(5th order Butterworth at 1 kHz)

# Sensors

## Accelerometers

- There is a total of 5 Accelerometer (Accs) installed on the suspension F0 of 2 different types
  - 3 Horizontal Accs
  - 2 Vertical Accs
- A model of the sensor mechanics and its disturbances has been developed in order to design the Kalman estimator and the controller.



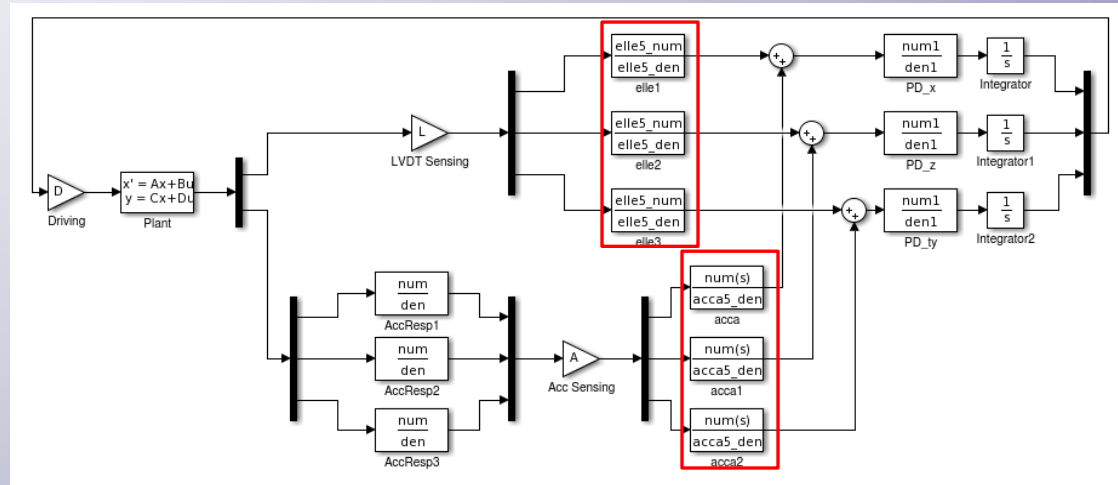
# Inertial Damping Overview

- Two loops based on traditional sensor blending are currently used to control IP motion:

## Horizontal Inertial Damping (ty, x, z)

6 x 3 plant matrix:  
(3 LVDTs + 3 Accelerometers) x 3 Coils  
on filter 0

3 x 3 Diagonalized Control matrix

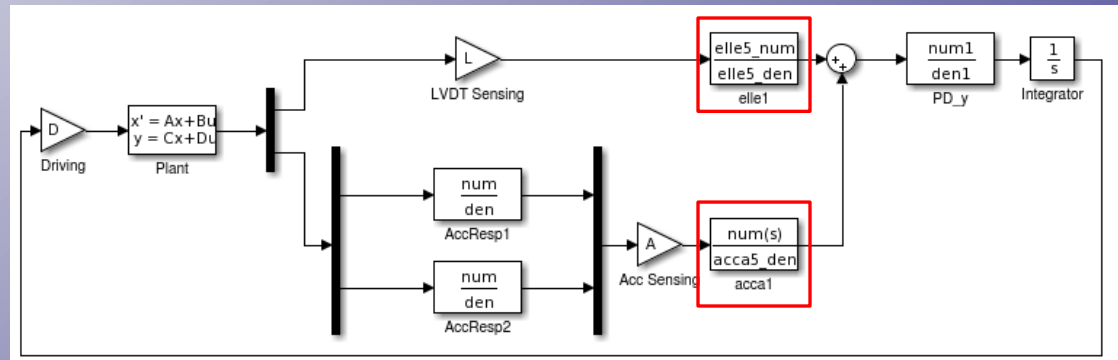


## Blending filters

## Vertical Inertial Damping (y)

3 x 2 control matrix:  
(1 LVDTs + 2 Accelerometers) x 2 Coils  
on filter 0

1 x 2 Diagonalized Control matrix

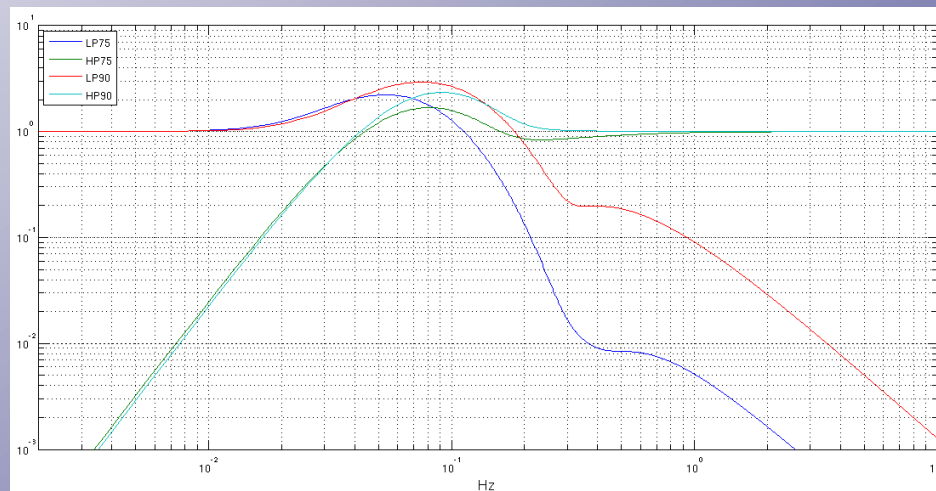
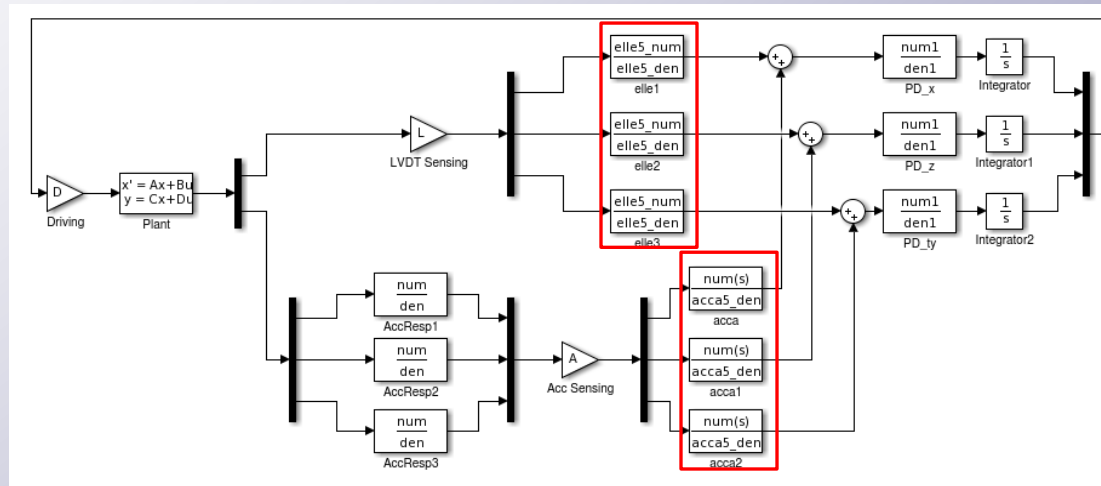


# Inertial Damping

## Standard Blending

Two Accelerometer-LVDT blending filters are used (High Pass for Accs and Low Pass for LVDTs)

- 75 mHz crossover frequency used for standard operation
- 90 mHz crossover frequency used for robustness (High microseism or windy conditions)



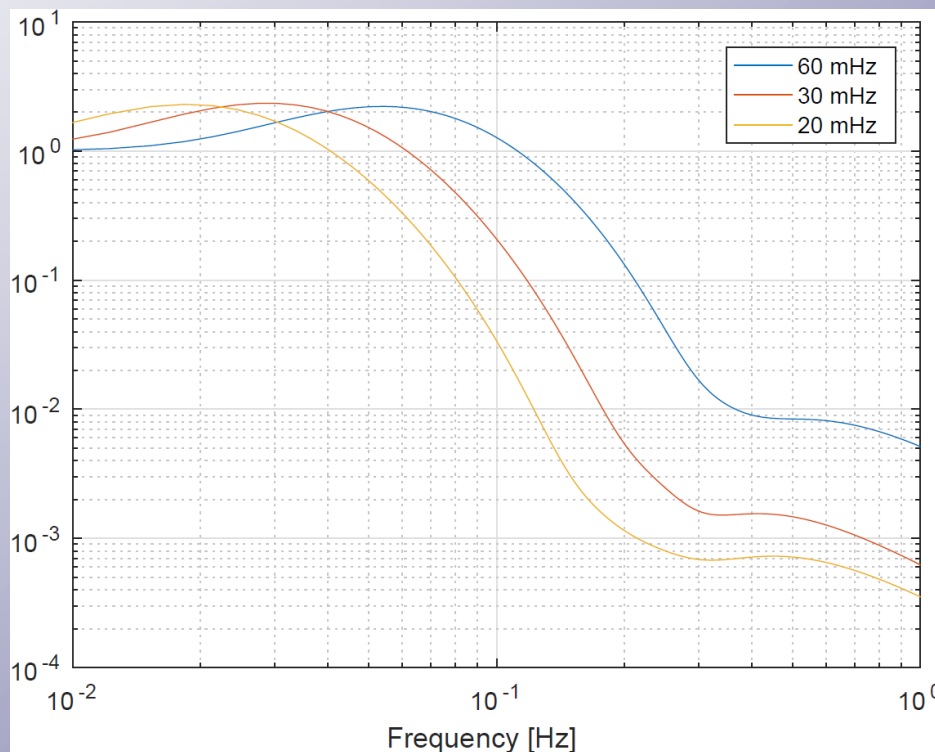
Standard Blending filters

# Inertial Damping

## GIPC

- Global Inverted Pendulum Control (GIPC) is a technique already used in VIRGO in which common and differential error signals are used to control the IP top stage instead of the local LVDTs and Accelerometers
- Using this strategy the crossover frequency of the blending filters can be lowered (20 mHz, 30 mHz) without losing robustness improving the rejection of microseism.

**Accelerometer low-pass filter comparison**



# F7 Control

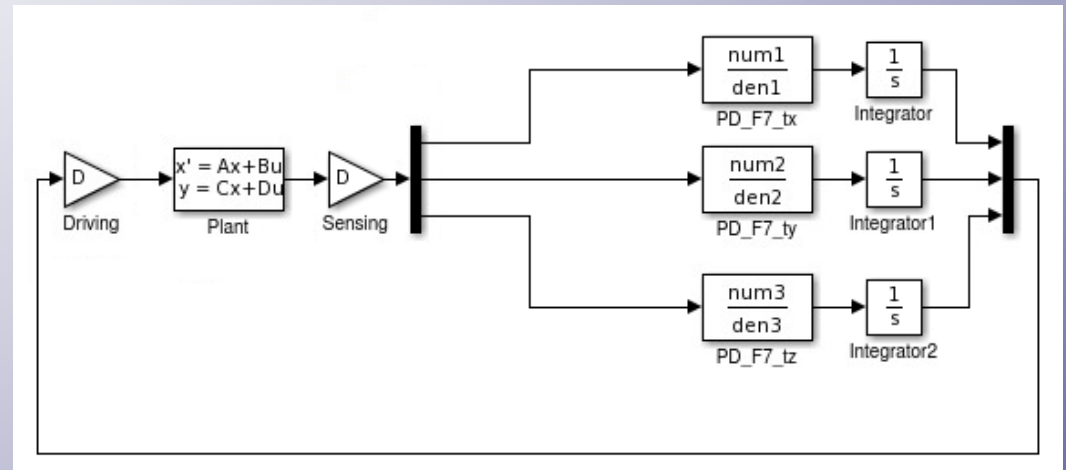
3 PID Filters are now used for the F7 control of all long suspensions.

## F7 Control (tx, ty, tz)

6 x 6 plant matrix:

6 LVDTs x 6 Coils on the F7

3 x 3 Diagonalized Control Matrix



- Tx and Tz filters are required to damp a 400 mHz payload mode.

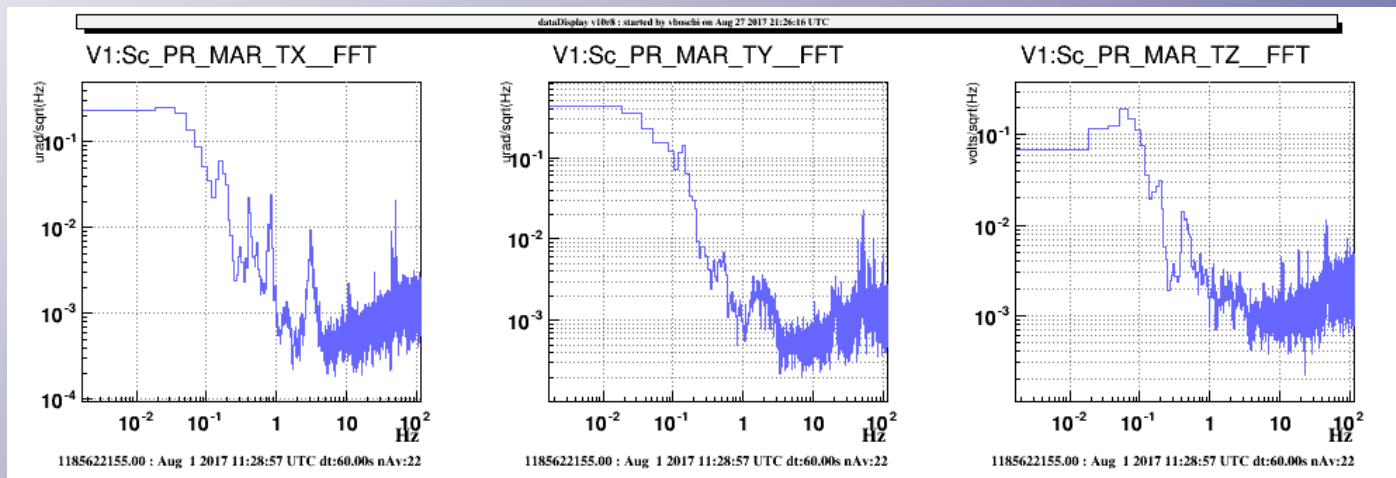
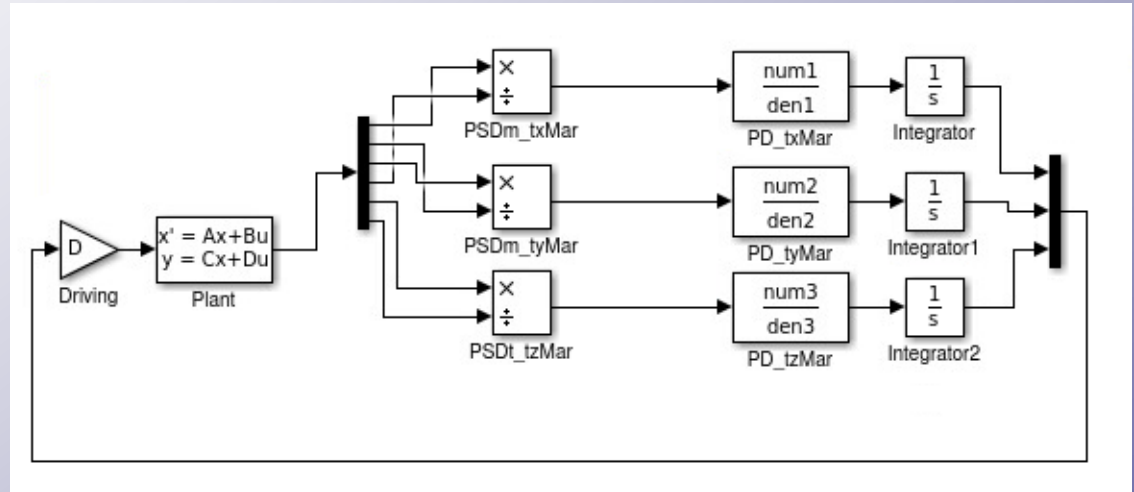
# Local Control

## Local Control (tx, ty, tz)

3 x 8 plant matrix:  
3 PSD signals x 8 Coils on Marionette

3 x 3 Diagonalized Control Matrix

Bang-bang control (Coarse)  
PID (Fine)



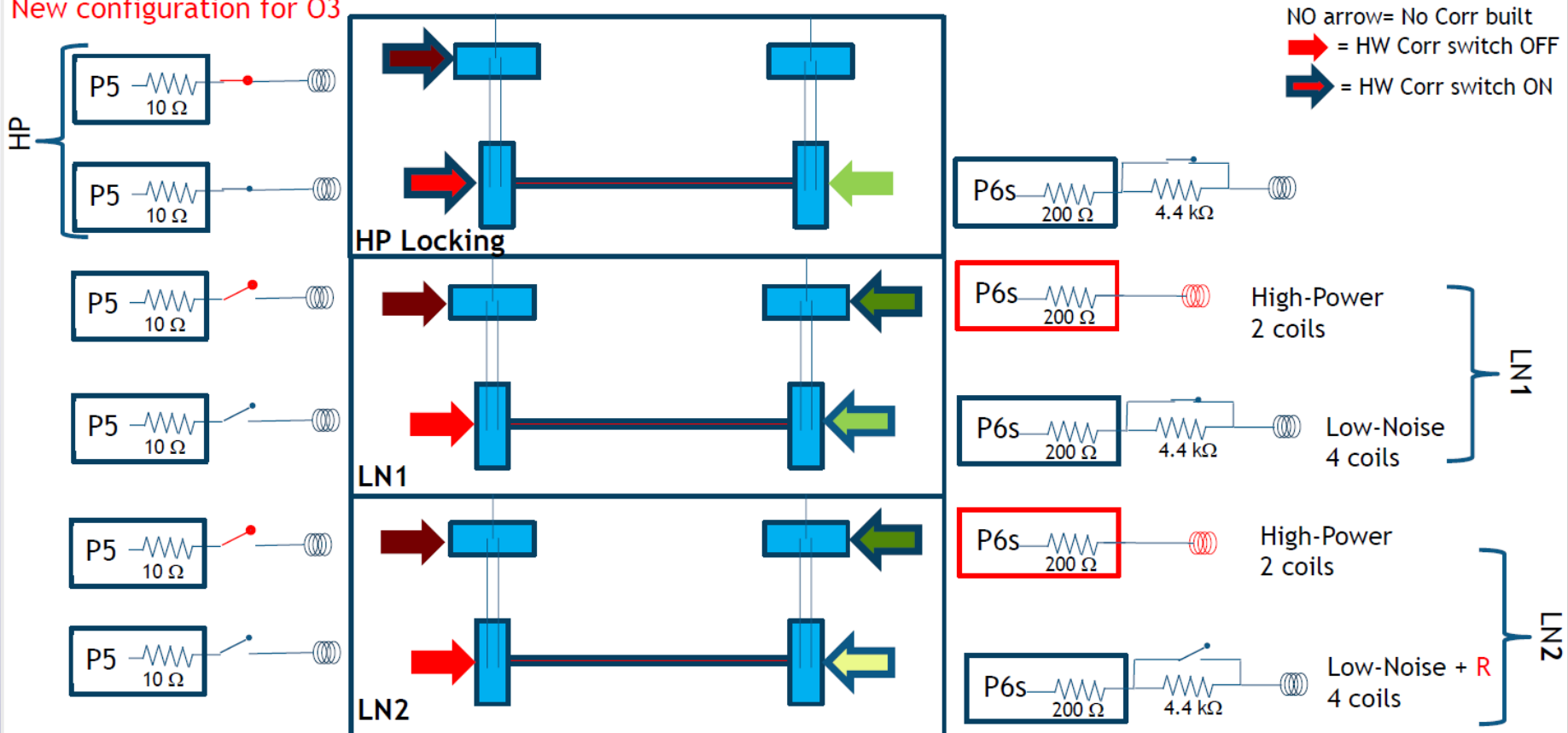
**A few nrad/sqrt(Hz) of spectral displacement above 1 Hz**

# Locking

Three mirror actuation modes are used:

- High power (10 Ohm output resistance) for lock acquisition only
- Low Noise 1 (200 Ohm output resistance + 1st order shaping filter)
- Low Noise 2 (4.6 kOhm output resistance + 1st order shaping filter)

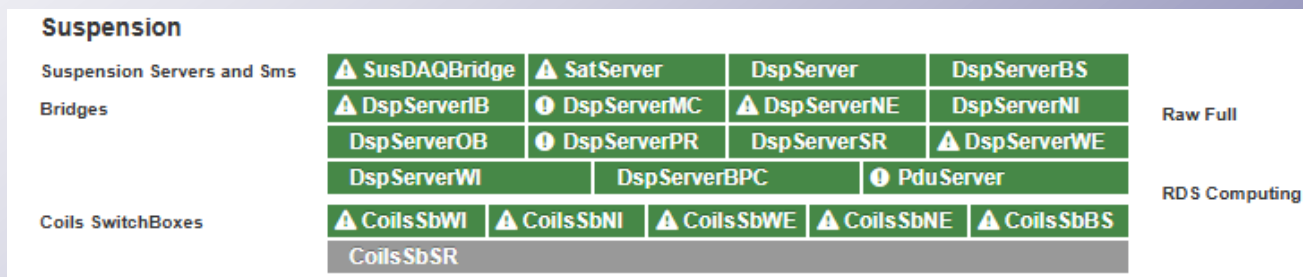
New configuration for O3



\* In the schematic is not shown an intermediate configuration that allows to insert a resistor at INPUT side to smooth ON/OFF

# Supervisor

- Supervisor is an important part of the subsystem since it allows to monitor the status of both hardware and software and to interact with the DSP from external code such as Python.
- SAT Supervising software used in O2 and O3 was based on TANGO. However, it was extremely complex to maintain and unstable.
- The supervisor has been fully re-written by Akis with more functionality, less complexity and more stability.



**DspServerIB** ▲ GPS:1435313646 - 2025-06-30 12:12:48: IB\_Sa\_41028 0x010 IB\_Sa\_43130 0x010 IB\_Sa\_31009 0x010 IB\_Sa\_43121 0x010 IB\_Sa\_41023 0x010

Application: /virgoApp/PySat/v3r3/scripts/PySatDspSrv.py  
Host: olserver130.virgo.infn.it Pid: 24675 Process uptime: 447 days and 1h09m07s  
🔗 Configuration: /virgoData/VirgoOnline/DspServerIB.cfg  
🔗 Log: /virgoLog/VirgoOnline/DspServerIB/DspServerIB\_2024-04-09-09h04m42-UTC.log

Reload Configuration Run checks Explain errors Activate DEBUG logging Activate INFO logging Activate WARNING logging

▲ Last most critical alert was: 2025-06-28 07h36m12 UTC Tower IB - Temperature error for DSP #51174: Sensor #1: 62.5 C.

ⓘ	2025-06-30 10h12m47 UTC	Tower IB - Temperature warning for DSP #43130: Sensor #0: 54.0 C, Sensor #1: 52.0 C.
ⓘ	2025-06-30 10h12m47 UTC	Tower IB - Temperature warning for DSP #31009: Sensor #0: 51.5 C, Sensor #1: 51.0 C.
ⓘ	2025-06-30 10h12m47 UTC	Tower IB - Temperature warning for DSP #43121: Sensor #0: 50.5 C.
ⓘ	2025-06-30 10h12m47 UTC	Tower IB - Temperature warning for DSP #41023: Sensor #0: 50.5 C.
ⓘ	2025-06-30 10h13m48 UTC	Tower IB - Temperature warning for DSP #41028: Sensor #0: 51.0 C.
ⓘ	2025-06-30 10h13m48 UTC	Tower IB - Temperature warning for DSP #43130: Sensor #0: 54.0 C, Sensor #1: 52.0 C.
ⓘ	2025-06-30 10h13m48 UTC	Tower IB - Temperature warning for DSP #31009: Sensor #0: 51.5 C, Sensor #1: 51.0 C.
ⓘ	2025-06-30 10h13m48 UTC	Tower IB - Temperature warning for DSP #43121: Sensor #0: 50.5 C.
ⓘ	2025-06-30 10h13m48 UTC	Tower IB - Temperature warning for DSP #41023: Sensor #0: 50.5 C.

**Thank you for your attention!!**

