ETH zürich

LTP FEE Closed Loop Simulator at ETHZ

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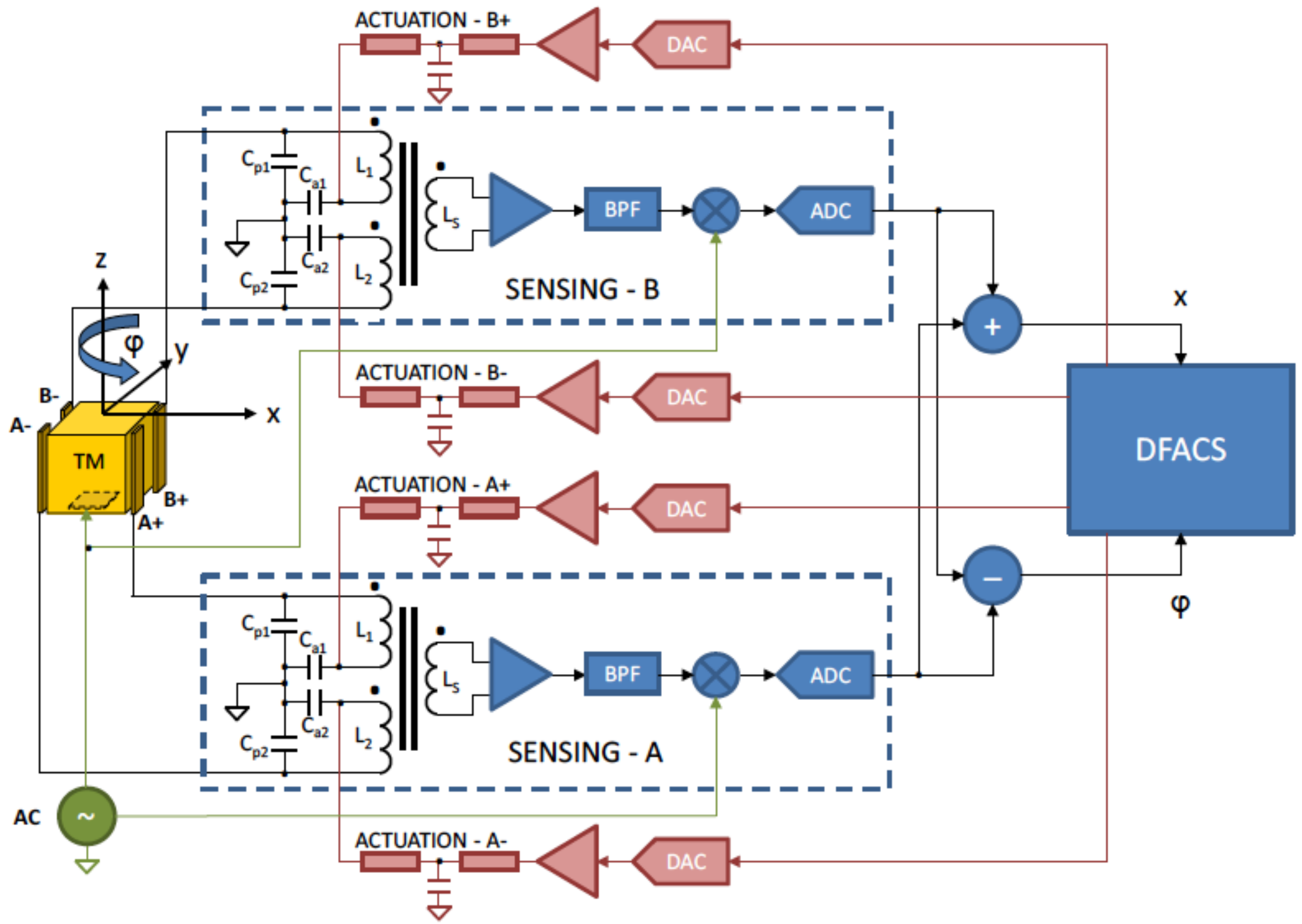
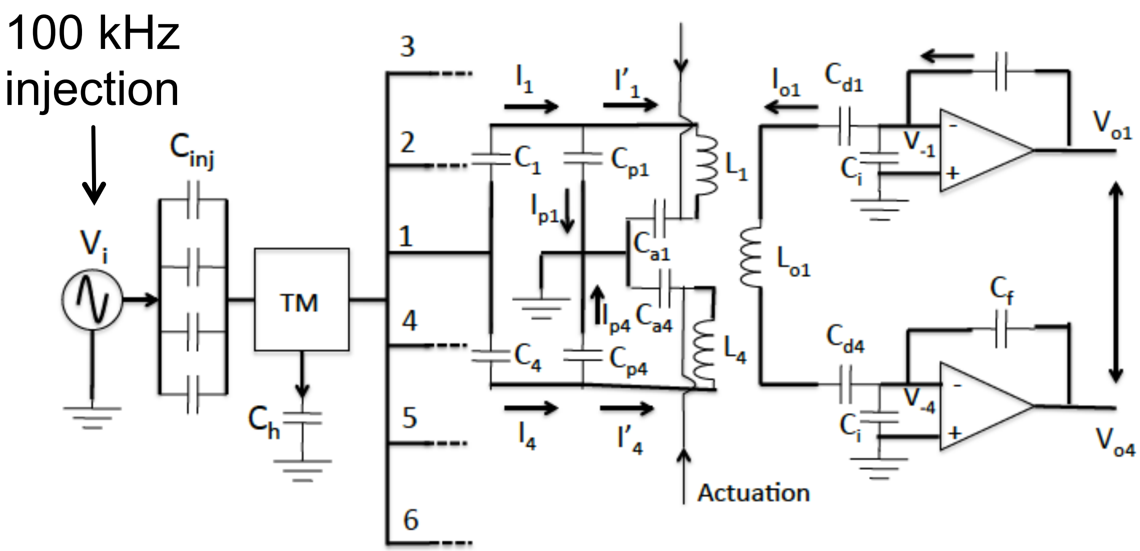
Why A New Simulator?

- We want an handy instrument for LTP FEE analysis
- We want it to be representative of the critical hardware details
- For that reason we need it to support non-linear features like multiplicative noise
- As a consequence we cannot just expand the LTPDA State Space Model simulator

LTP Front End Electronics (FEE)



Sensing Bridge



Resonance inductive coupling

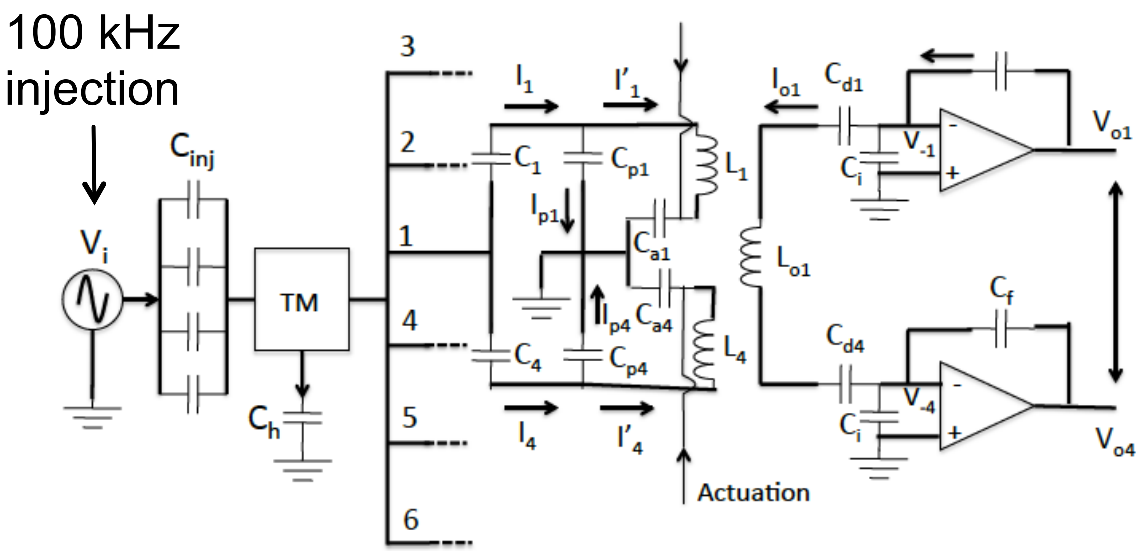
Resonance is tuned by C_{pi}

At resonance we have the best displacement to voltage gain and best SNR

Key elements for the simulation:

- Noise
- Offset
- Measurement band equivalent (simulation run @ 10 Hz)

Sensing Bridge - Offset



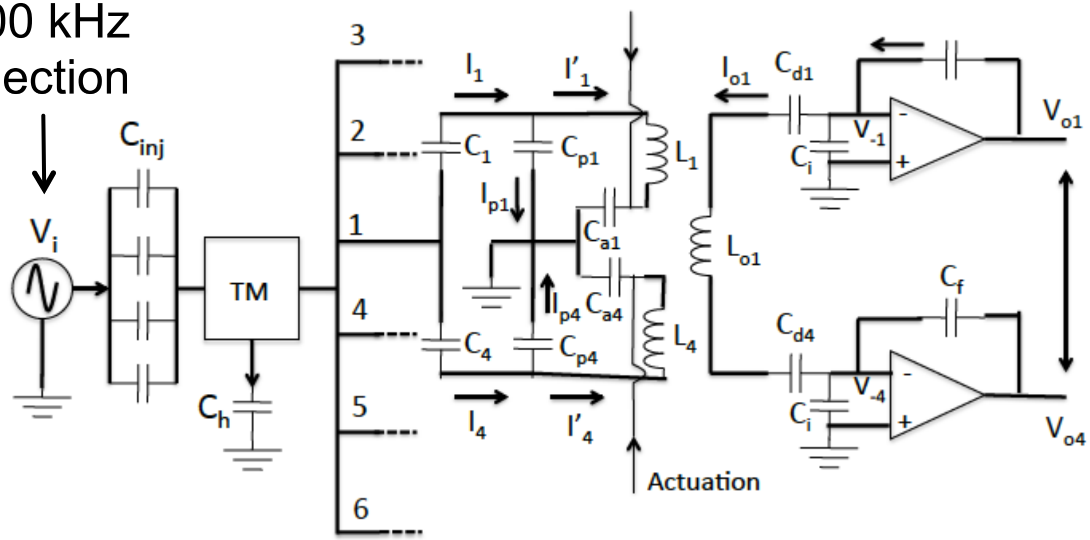
$$V_{bridge} \sim \underbrace{C_0\,\Delta H\,V_{TM}}_{\text{Offset}} + \underbrace{\Delta C\,2\hat{H}\,V_{TM}}_{\text{Displacement Readout}} \qquad V_{TM} \propto V_i$$

Offset determined by:

- Asymmetry of transformer primary windings
- Asymmetry of transformer primary to secondary couplings
- Asymmetry of bridge resonance tuning capacitors
- Asymmetry of actuation filter capacitors

Sensing Bridge - Noise

100 kHz injection



$V_{bridge} \sim C_0 \, \Delta H \, V_{TM} + \Delta C \, 2\hat{H} \, V_{TM}$ $V_{TM} \sim V_i$

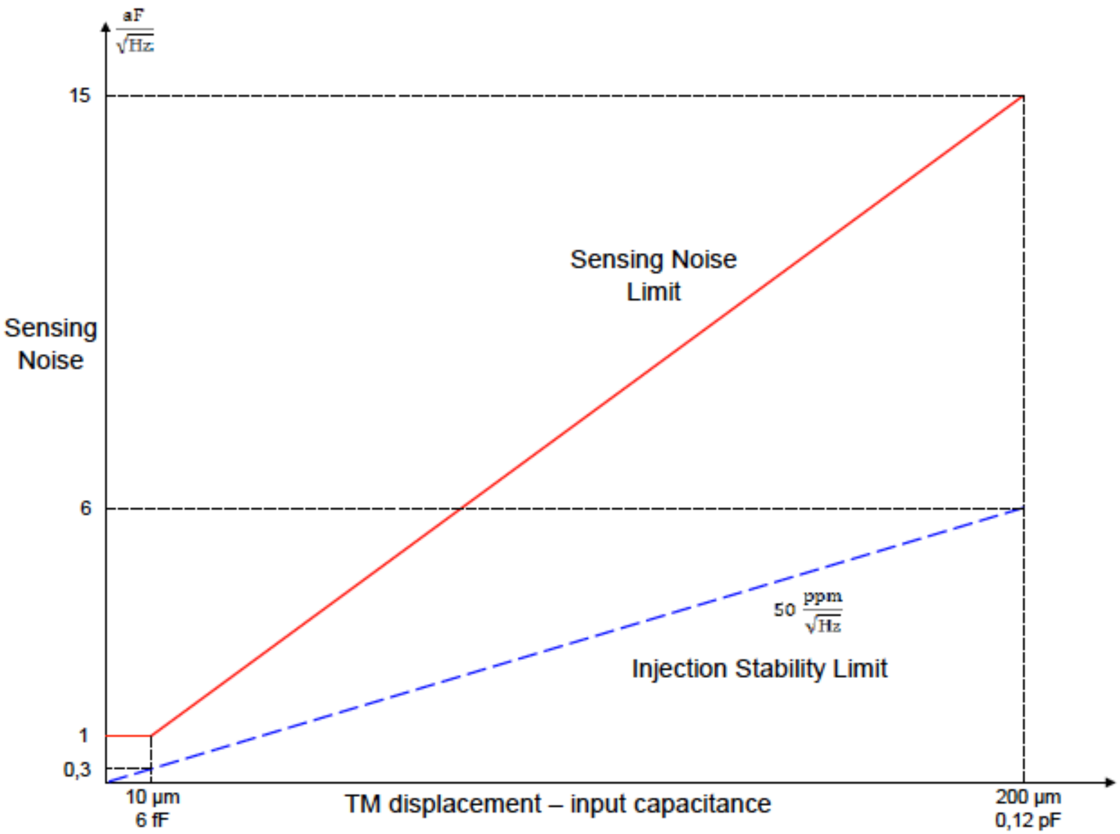
Offset

Displacement Readout

Principal noise sources:

- Voltage reference instability on V_i determines a coherent multiplicative noise on all the channels
- Thermal noise in dispersive elements of the circuit dominated by the quality factor of the transformer bridge
- Op. Amp. Noise that is minimized at the resonance

Sensing Bridge - Noise



Requirement for the sensing noise in High Resolution mode

Requirement is flat in performance range, i.e. the first 10 µm in displacement. Then it is multiplicative with the displacement.

Injection instability is supposed to account up to a 30% of the total noise budget

Voltage reference noise has a typical 1/f noise shape that is the main source of the multiplicative noise

Sensing Bridge – Noise – Current implementation

Three noise sources:

1/f Voltage reference noise

$$\left[N_{th}(f) + \gamma \frac{N_{V_{TM}}(f)}{C_f} (\beta + \alpha \Delta C) \right]$$

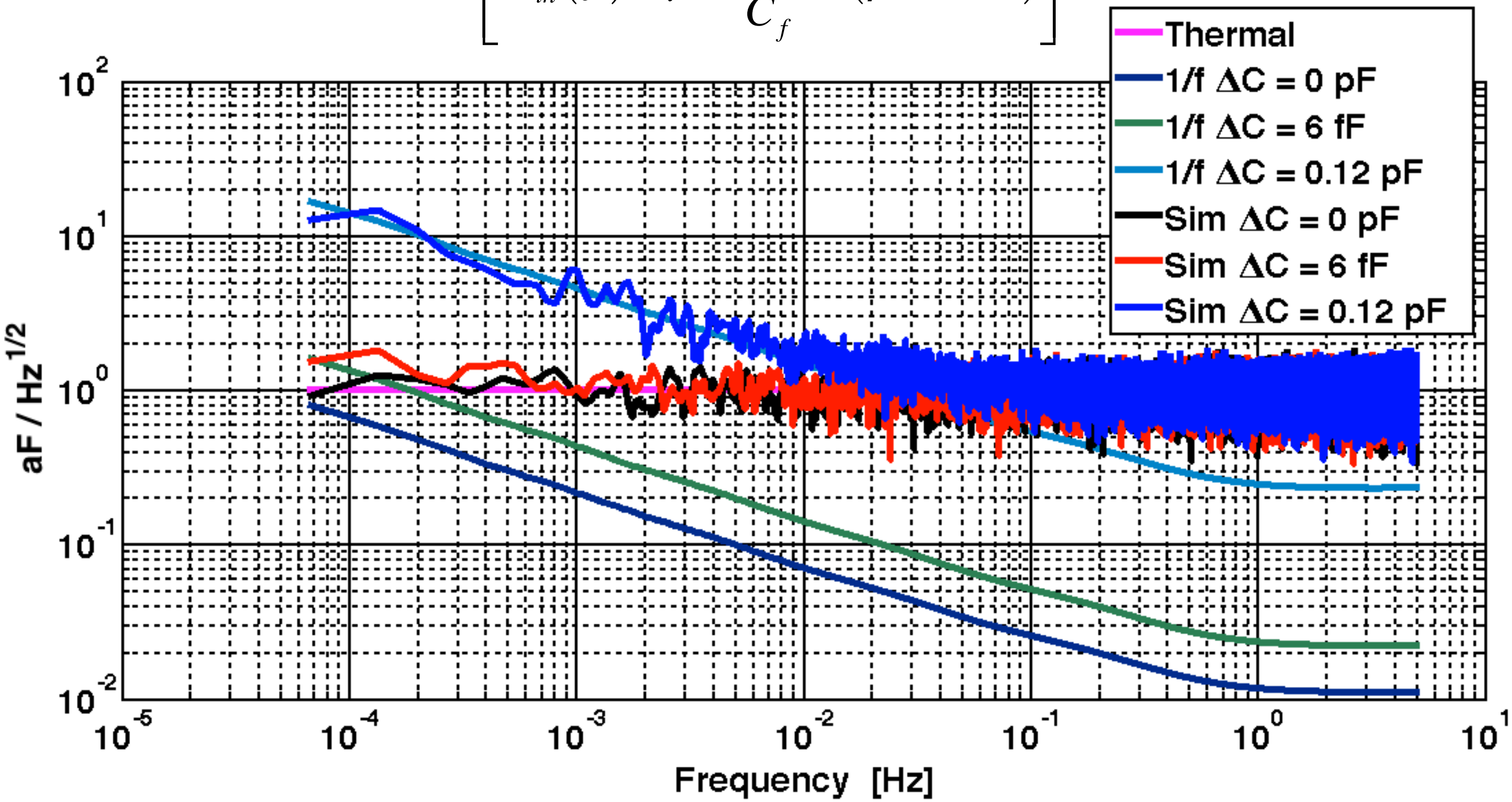
Thermal
Req: 1 aF/√Hz

Multiplicative, on if $V_{inj} \neq 0$
Limit: 50 ppm/√Hz

Always on when $V_{inj} \neq 0$
Limit: 0.3 aF/√Hz

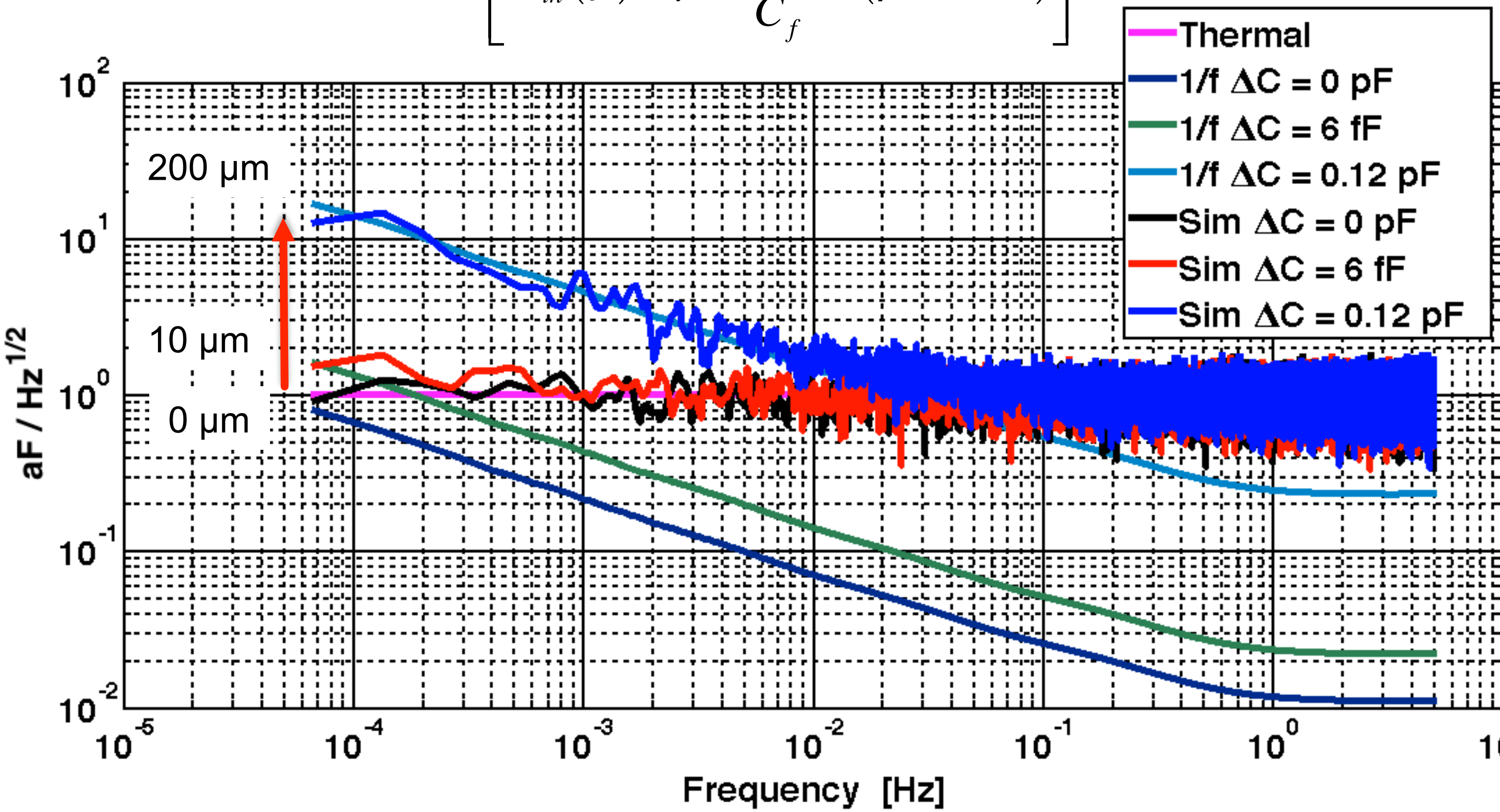
Sensing Bridge – Noise – Current implementation (work in progress!)

$$\left[N_{th}(f) + \gamma \frac{N_{V_{TM}}(f)}{C_f} (\beta + \alpha \Delta C) \right]$$

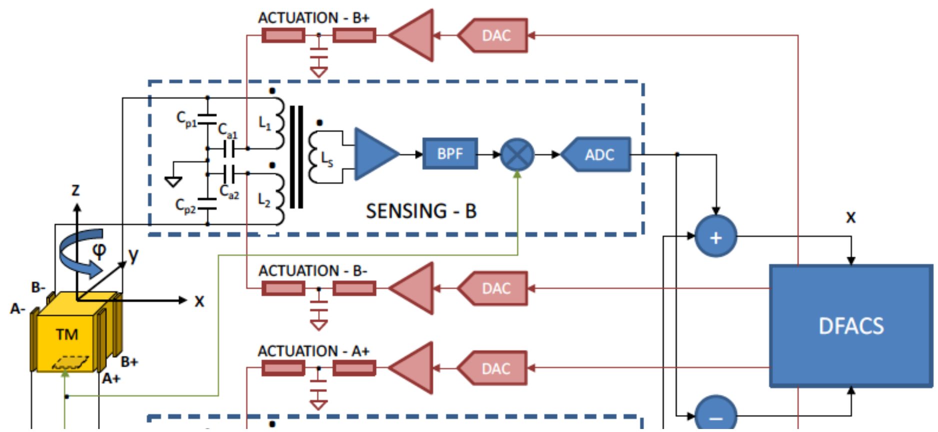


Sensing Bridge – Noise – Current implementation

$$\left[N_{th}(f) + \gamma \frac{N_{V_{TM}}(f)}{C_f} (\beta + \alpha \Delta C) \right]$$



Sensing – Demodulator + Lowpass



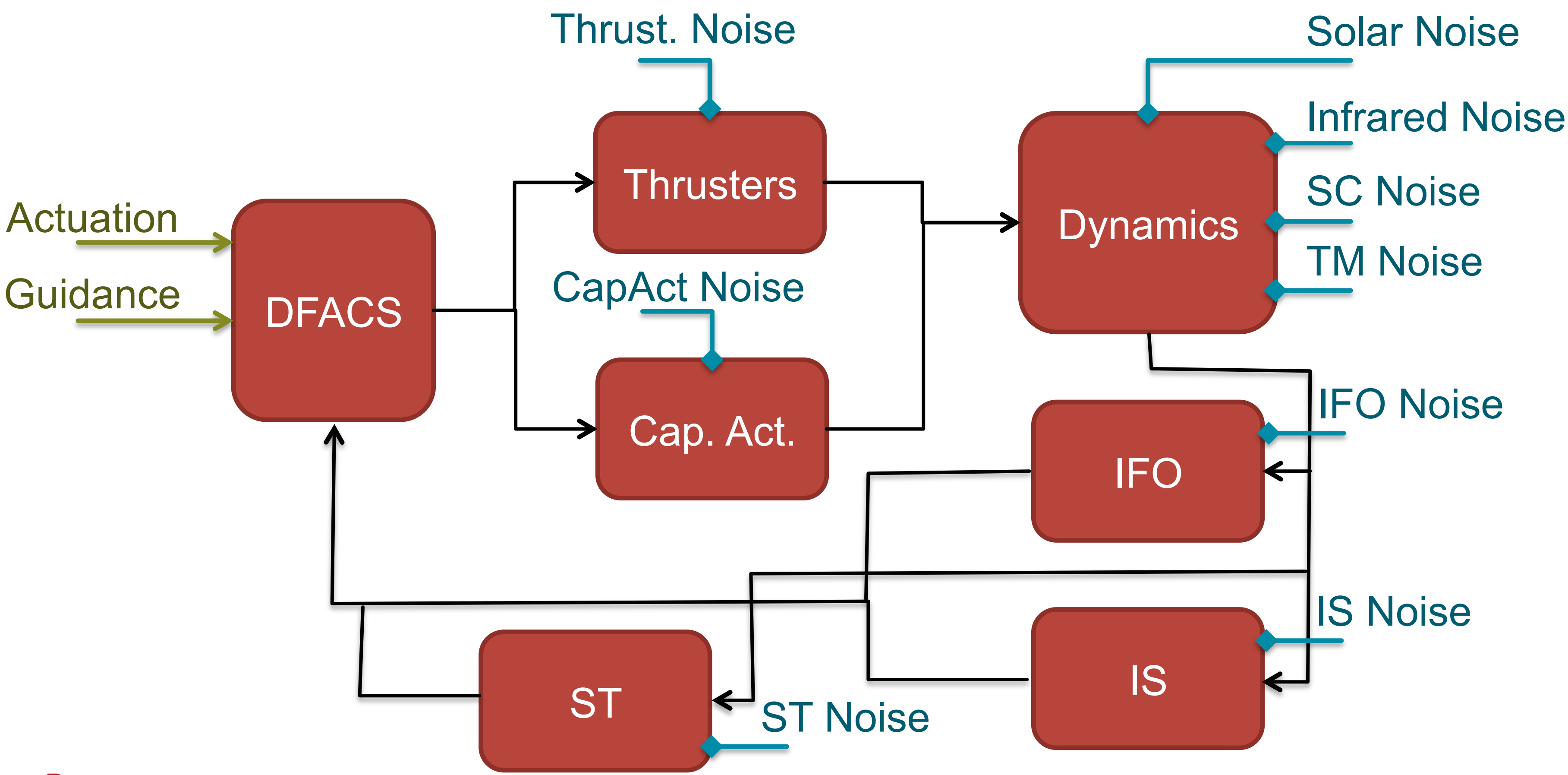
- Signals are amplitude modulated at f_c = 100 kHz
- Low frequency signals at f show a double sideband signal in the fourier transform with components at f_c – f and f_c + f
- Demodulation process, multiply the signal by a pure sine / cosine at the carrier frequency
- The process provides a low frequency signal V(t) + a $2f_c$ signal ~$V(t)\cos(2\omega_c t)$
- High frequency signal is removed by a lowpass filer
- The bandwidth of V(t) is half of the modulated signal, therefore noise density of the demodulated signal is twice that of the modulated signal

Sensing Simulator Requirements

- Knobs for the parameters responsible for the sensor offset
- Knobs for the parameters of the different noise sources
- Implementation of multiplicative noise (that is a non-linear process)
- Reasonable amount of system details in order to allow an effective analysis of the flight hardware

LTPDA Tools

Linear Closed Loop State Space Model



LTPDA State Space Models

Pros

- Closed loop
- Include realistic model for the DFACS
- Fast execution
- Several noise models
- Modular, can be easily extended / improved

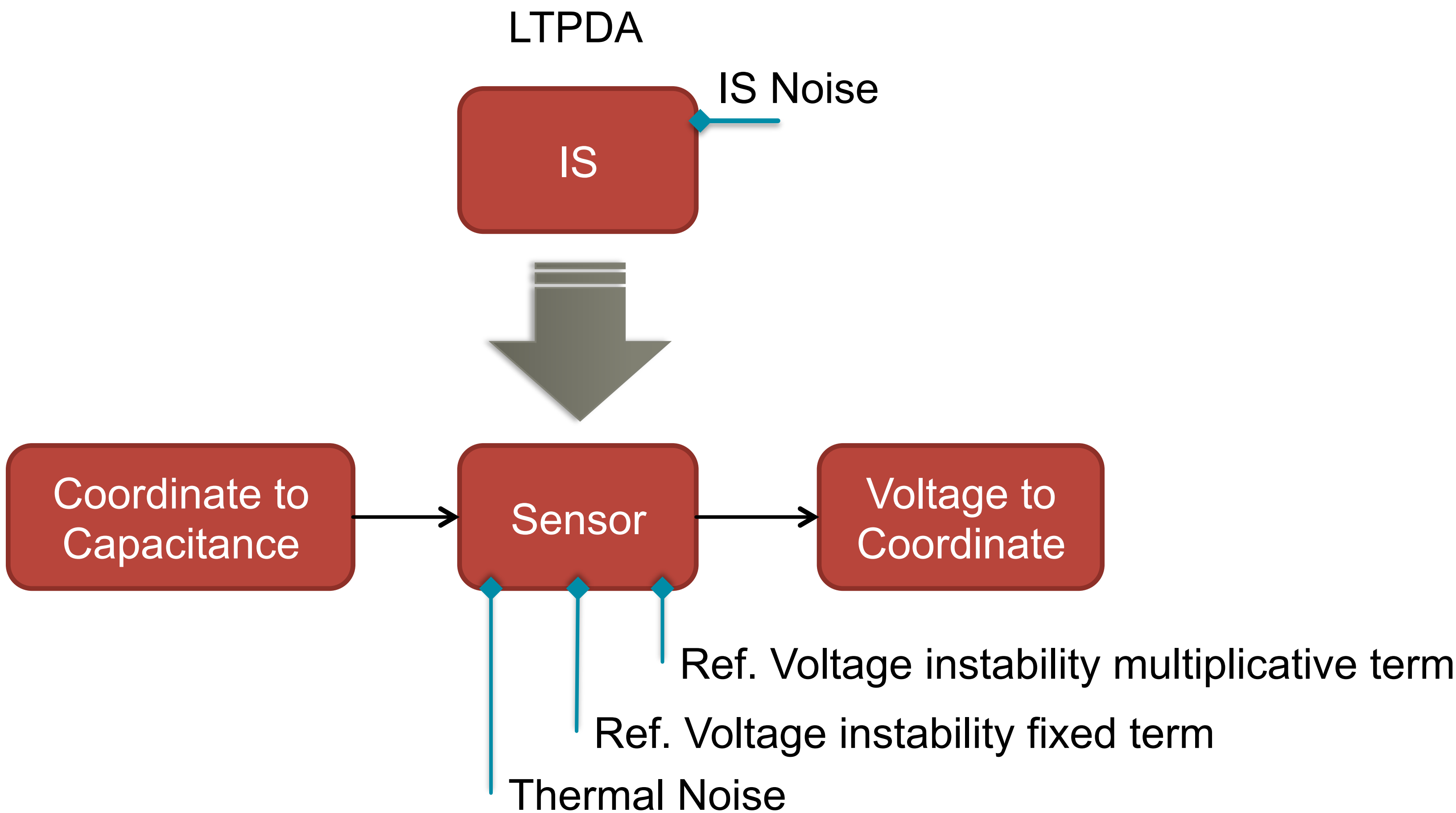
Cons

- Linear
  - Multiplicative noise cannot be implemented

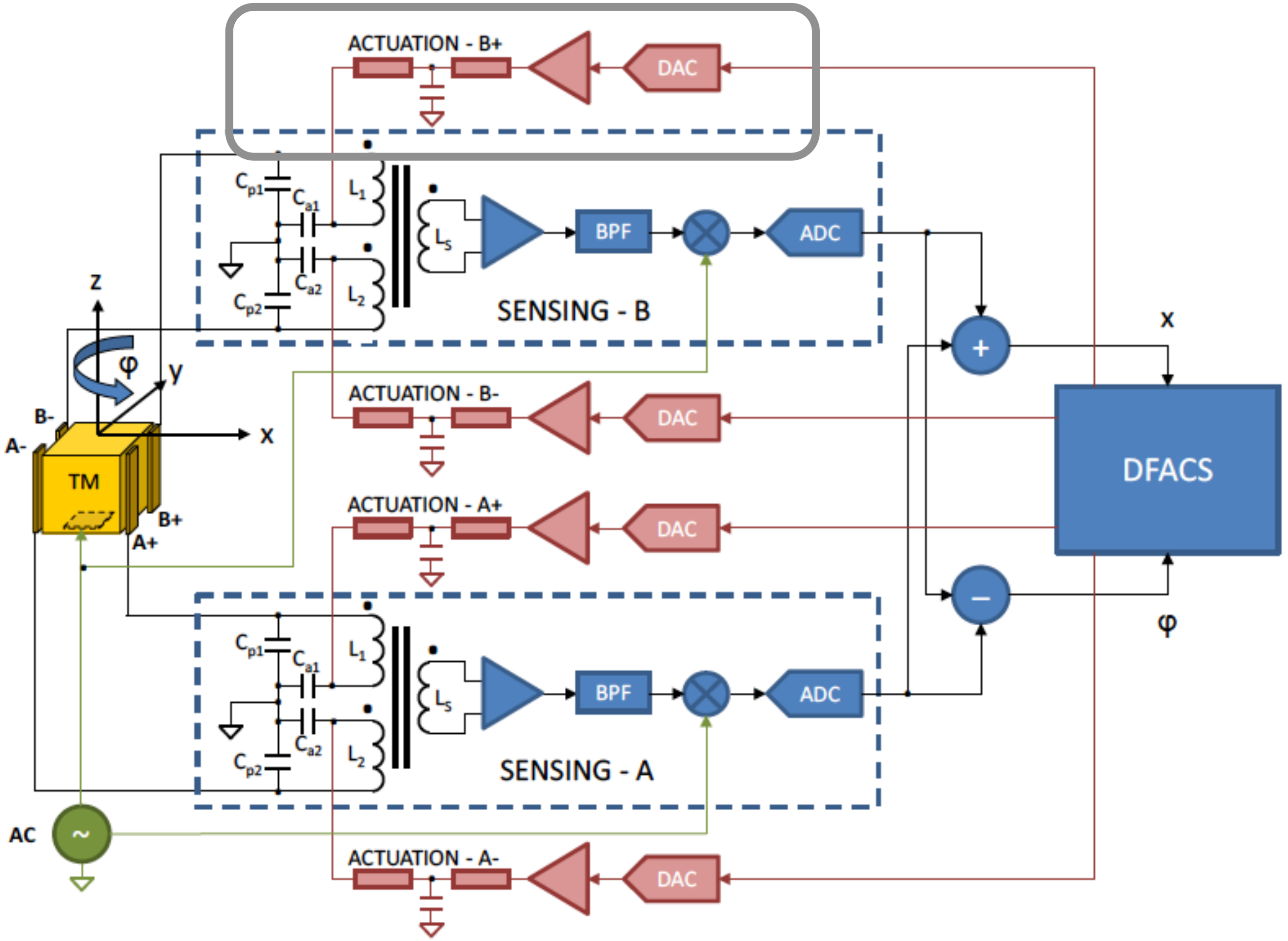
Hybrid Solution

- LTPDA SSM models for the linear subsystem
  - Extract State Space A, B, C, D matrices from the models
- MATLAB functions for non-linear systems (FEE GRS and Actuation)
- Combine in a time domain simulator

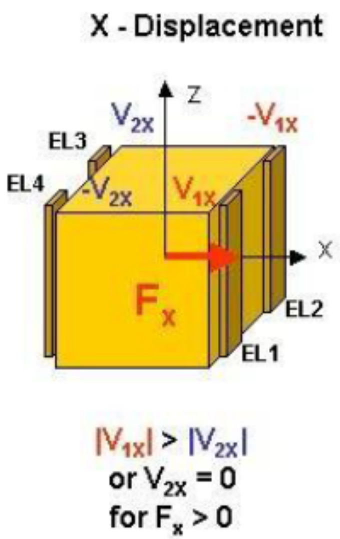
ETHZ FEE Sensor model vs. LTPDA

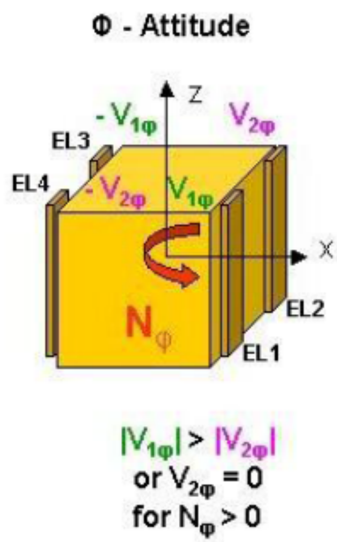


LTP Front End Electronics - Actuation



Actuation Scheme





$$V_1 = V_{1x}\sin(\omega_x t) + V_{1\varphi}\sin(\omega_\varphi t) + V_{1DC}$$
$$V_2 = -V_{1x}\sin(\omega_x t) + V_{2\varphi}\cos(\omega_\varphi t) + V_{2DC}$$
$$V_3 = V_{2x}\cos(\omega_x t) - V_{1\varphi}\sin(\omega_\varphi t) + V_{3DC}$$
$$V_4 = -V_{2x}\cos(\omega_x t) - V_{2\varphi}\cos(\omega_\varphi t) + V_{4DC}$$

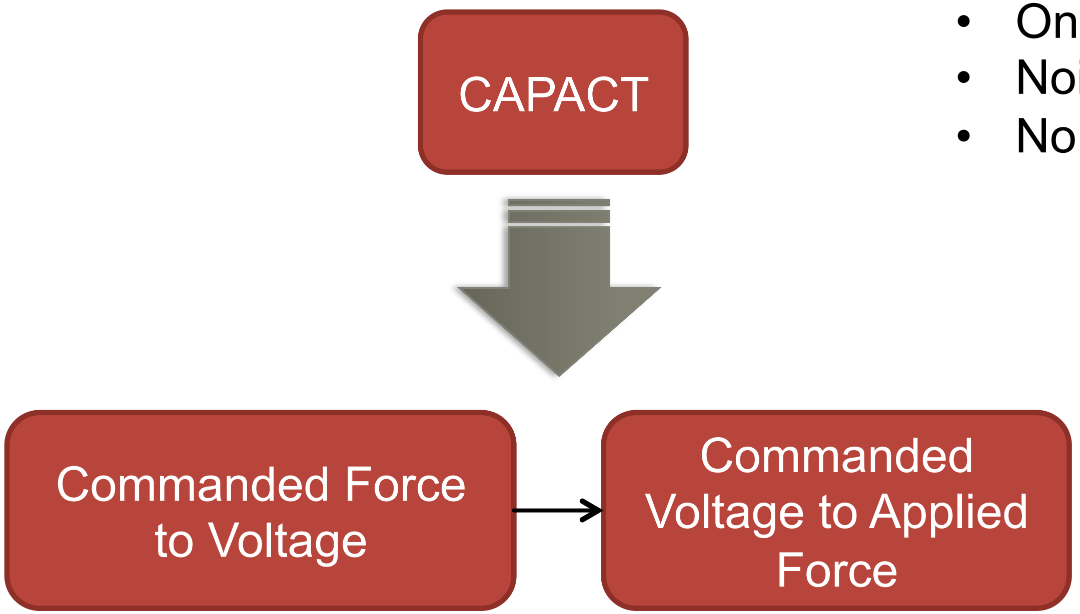
- Constant Stiffness
- Neutral TM

$$V_{1x} = \frac{1}{2}\sqrt{\frac{d_x}{C_{0x}}}\sqrt{2F_x + 2F_{\max,x}}$$
$$V_{2x} = \frac{1}{2}\sqrt{\frac{d_x}{C_{0x}}}\sqrt{-2F_x + 2F_{\max,x}}$$
$$|\omega_{xx}^2| = \frac{2}{d_x}F_{\max}$$

Actuation – Noise Analysis

- Multiplicative noise due to actuation waveform instability in Measurement Bandwidth (MBW). Can be correlated (voltage reference), uncorrelated (thermal instability of the electronics)
- Down conversion (in the MBW) of additive voltage noise at the actuation frequency. Amplitude modulated process: $S(f) \sim \frac{1}{4} [S_n(f-f_c) + S_n(f+f_c)] \sim \frac{1}{2} S_n(f_c)$ since $f << f_c$
- Coupling of additive voltage noise with DC voltages and TM Charge
- TM Charge is itself a noisy process

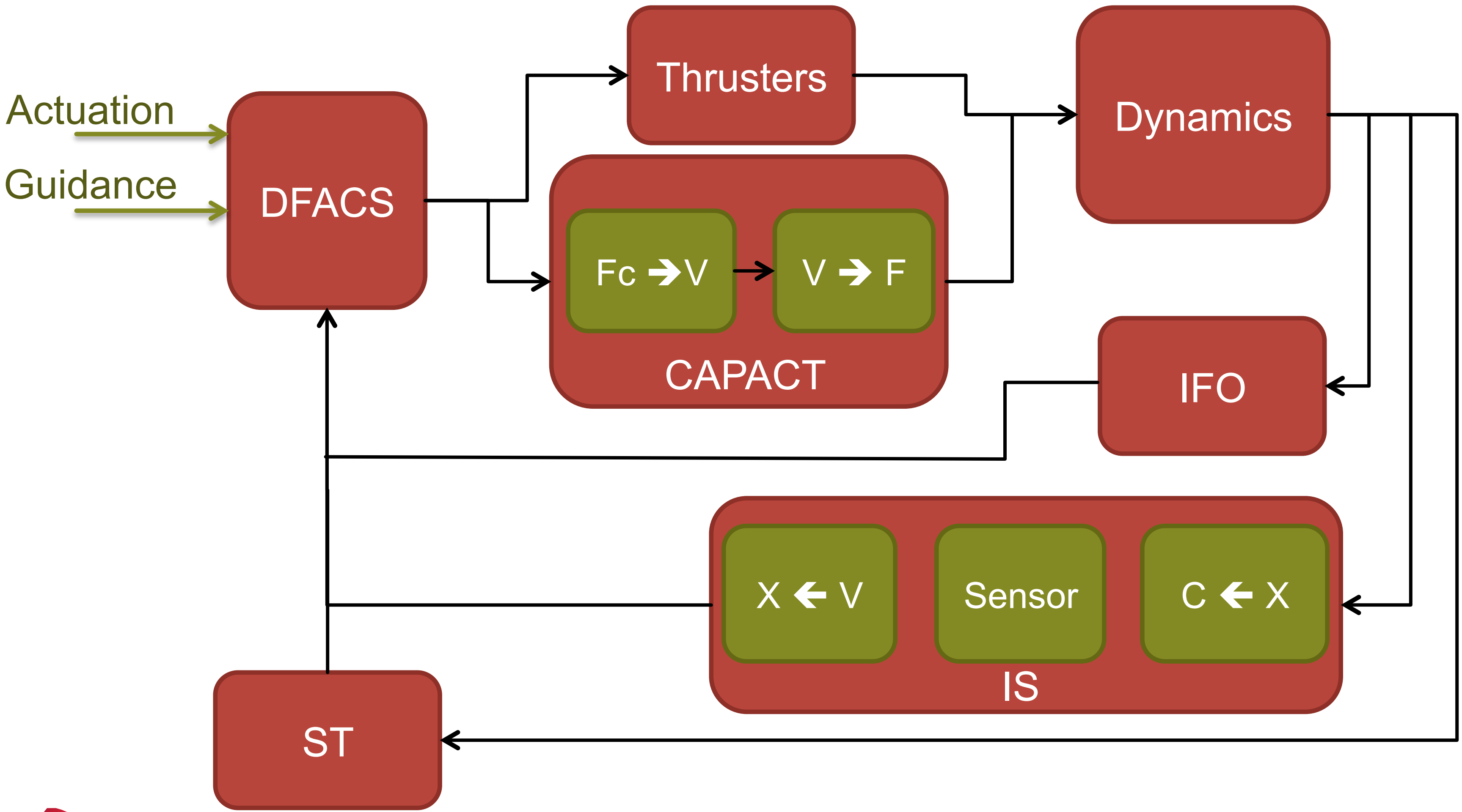
Standard LTPDA SSM vs. ETHZ implementation



- One noise shaping filter per channel
- Noise gain can be controlled
- No TM Charge

- Support the different noise sources
- Noise gain can be controlled
- Support TM Charge

ETHZ Simulator



Work in progress

- Introduce noise from Digital to Analog (and Vice Versa) converter
- Model the effect of the ΣΔ loop, perhaps as a noise source
- Implement Wide Range mode (corresponding to Accelerometer mode)