Design of a Low-Power Potentiostatic Second-Order CT Delta-Sigma ADC for Electrochemical Sensors

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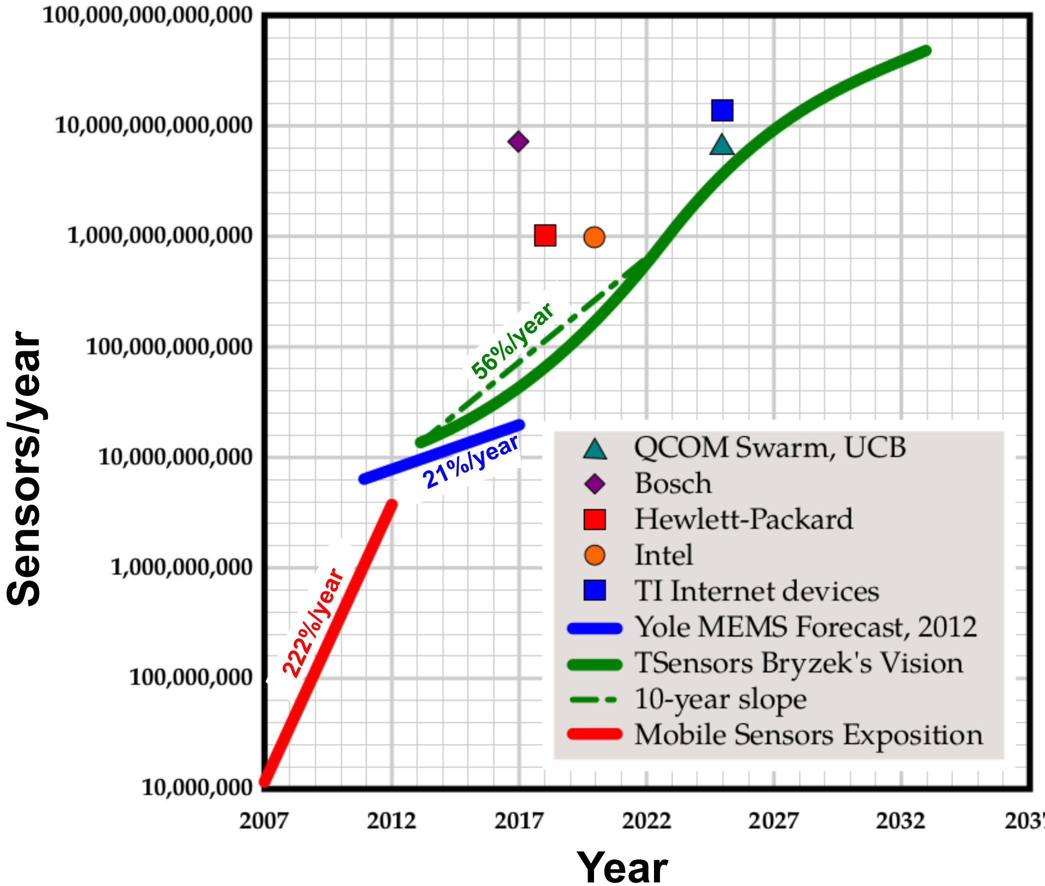
Trillion-Sensor Vision

- Several organizations created visions for continued growth to trillion(s) sensors
  - $15 trillion by 2022
- **Electrochemical sensors** are growing exponentially due to potential of miniaturization and mass production
  - **Monolithic** or **hybrid** integration onto CMOS platforms
  - Applications in biosensors, quality control, ...

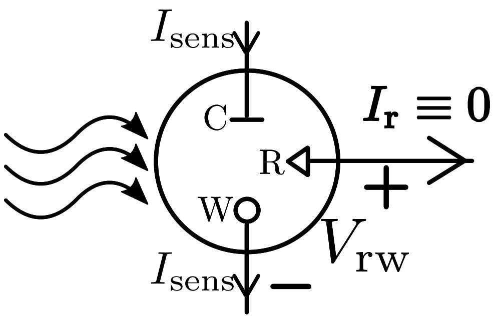


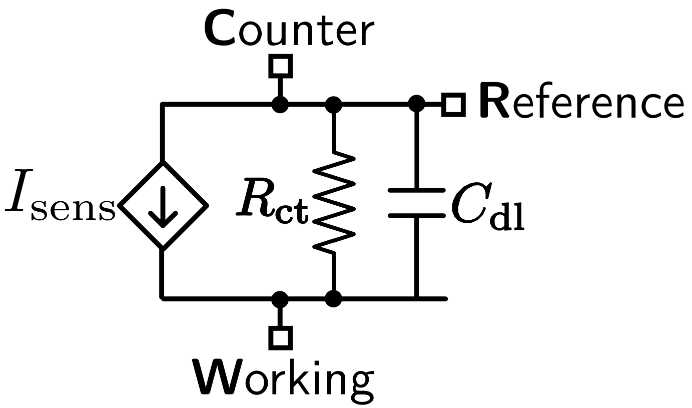
Expected sensor production growth per year

www.tsensorssummit.org

Amperometric Electrochemical Sensors

- ▲ Interaction with microorganisms
- ▲ **Selectivity** by functionalization
- ▼ Reduced **speed** and **life** time
- ▼ **Potentiostatic** and **amperometric** operations
- ▶ **Three electrodes:**
  - **W**orking
  - **R**eference
  - **C**ounter
- ▶ Measurement independent of the **R** and **C** impedances.





- Electrochemical **time constant:**

$$\tau_{ch} = R_{ct} C_{dl} \approx 10^{-1} s$$

Rct = charge-transfer resistance

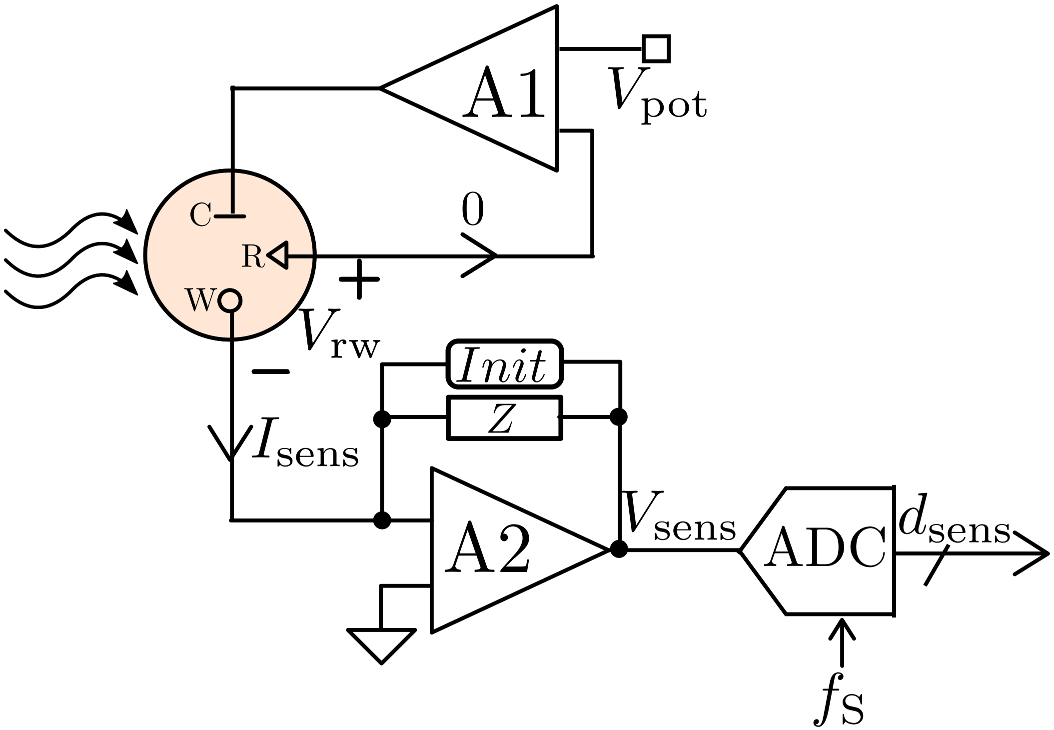
Cdl = double-layer capacitance

Classic circuit implementation

- **Potentiostat**
  - A_1 establishes the control loop to accomplish potentiostat operation

    $$V_{\mathbf{rw}} = V_{\mathbf{pot}} \quad \& \quad I_{\mathbf{r}} \equiv 0$$

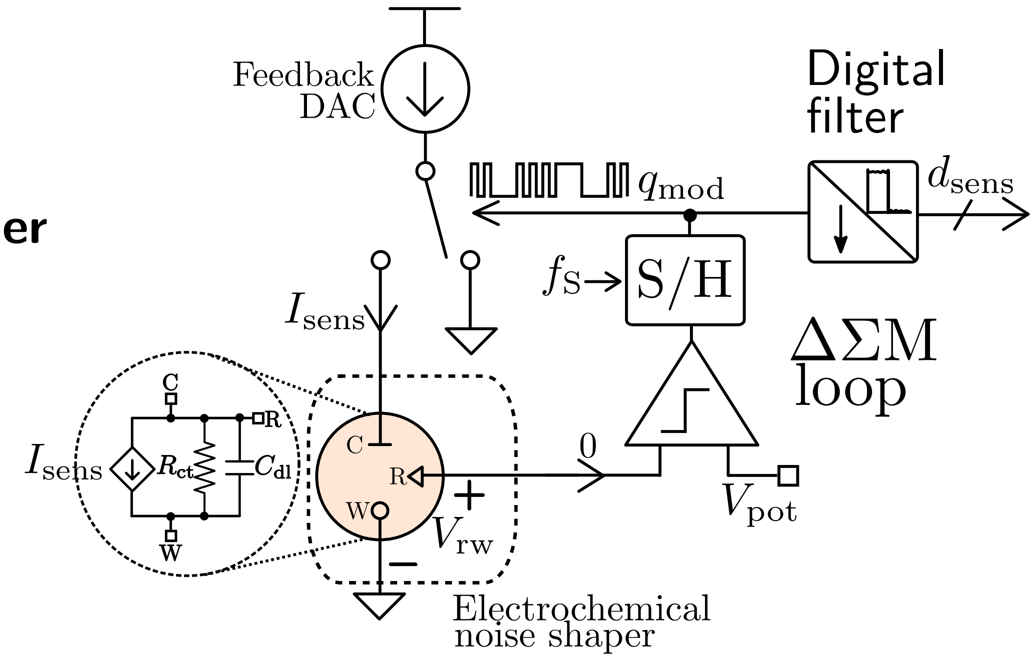
- **Amperometry**
  - A_2 converts sensor current to voltage for digitization and readout



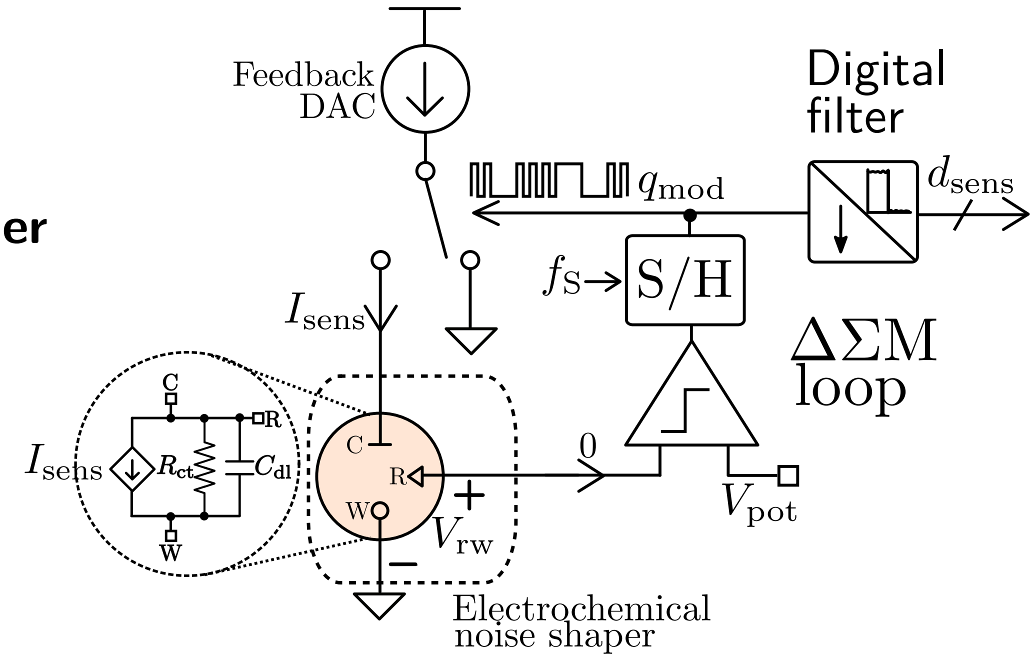
- ▼ Requires multiples OpAmps + ADC
- ▼ Large **area** and **power consumption**

Potentiostatic $\Delta\Sigma M$

- Behaviour similar to **low-pass first-order single-bit CT** $\Sigma\Delta M$ A/D modulator
- Error current converted into voltage and shaped in frequency by the **electrochemical sensor** itself
- High oversampling ratios (**OSR>100**) can be easly obtained with kHz-range clock frequencies f_S
- **Amperometric** read-out through the $\Delta\Sigma$ modulation of output bit stream q_{mod} by chemical input I_{sens}



Potentiostatic ΔΣM



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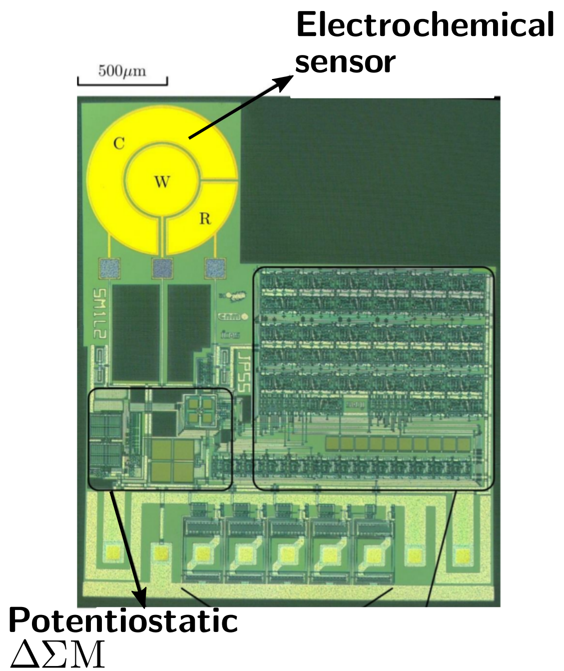
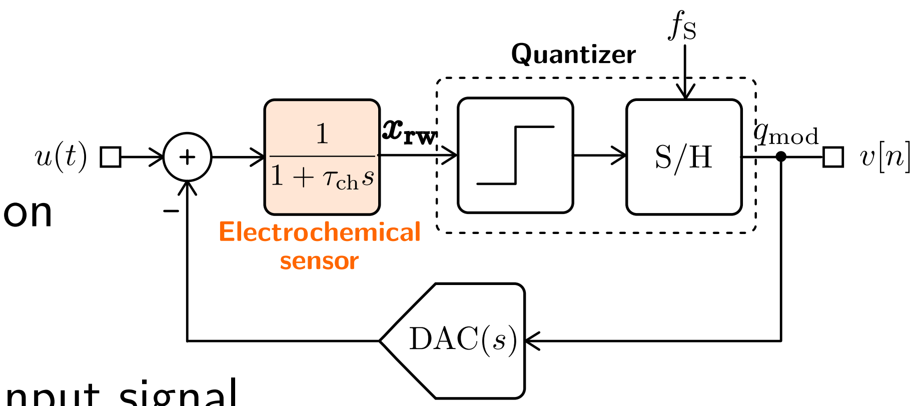
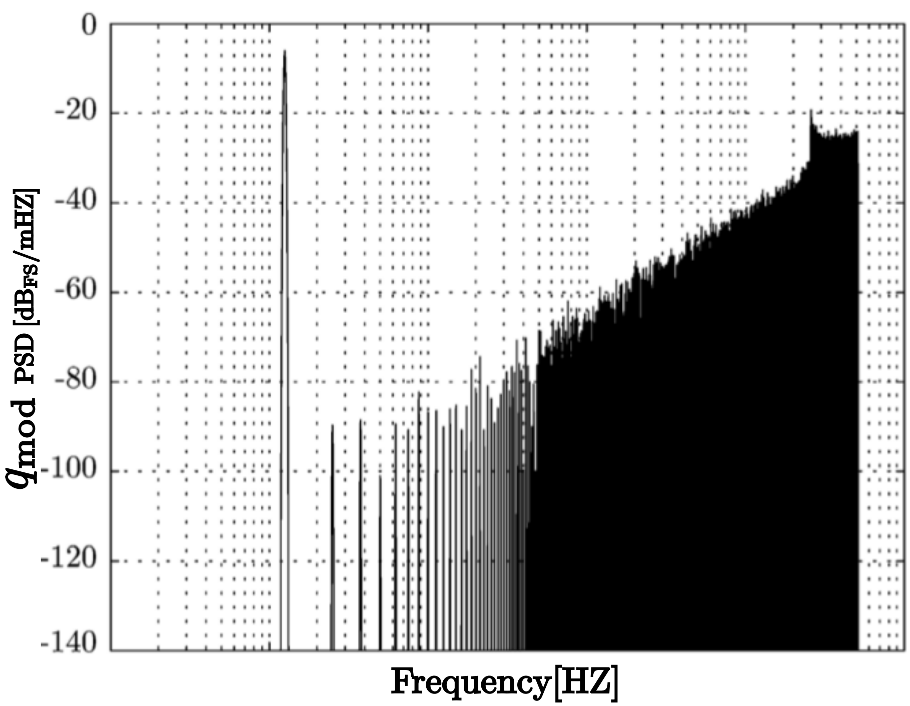
- High oversampling ratios (**OSR>100**) can be easily obtained with kHz-range clock frequencies f_S
- **Amperometric** read-out through the $\Delta\Sigma$ modulation of output bit stream q_{mod} by chemical input I_{sens}
- **Monolithic CMOS integration**
  Inexpensive 2.5μm in-house CMOS technology (CNM25) developed by ICAS group at IMB-CNM(CSIC)

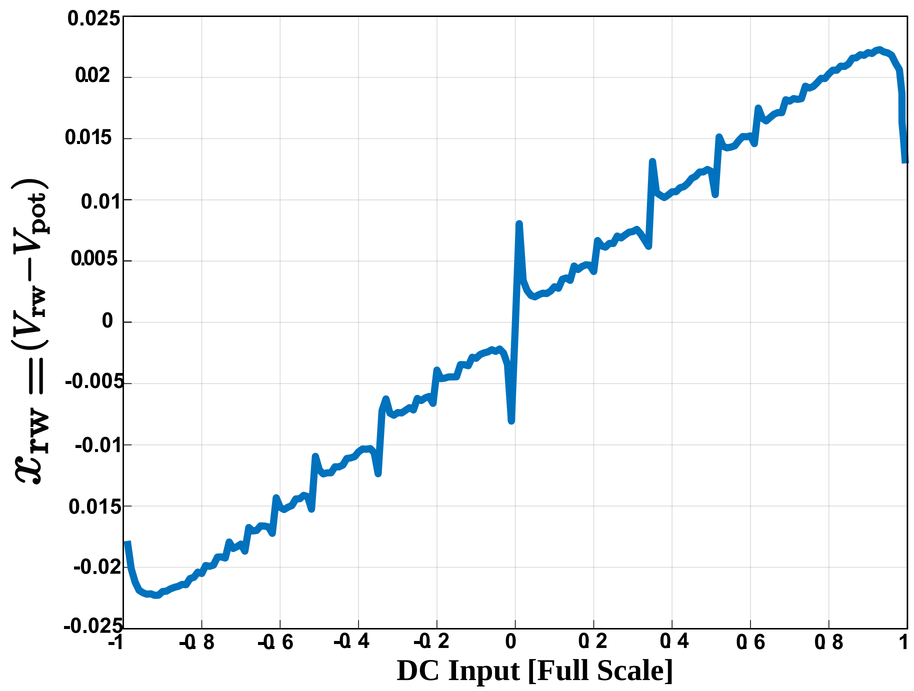


Potentiostatic ΔΣM

- Typical **tonal component** of 1st order ΔΣM
  - Quantization error and input signal correlation
- **Potentiostat operation** not well-defined
  - Potentiostatic error x_{rw} influenced by the input signal

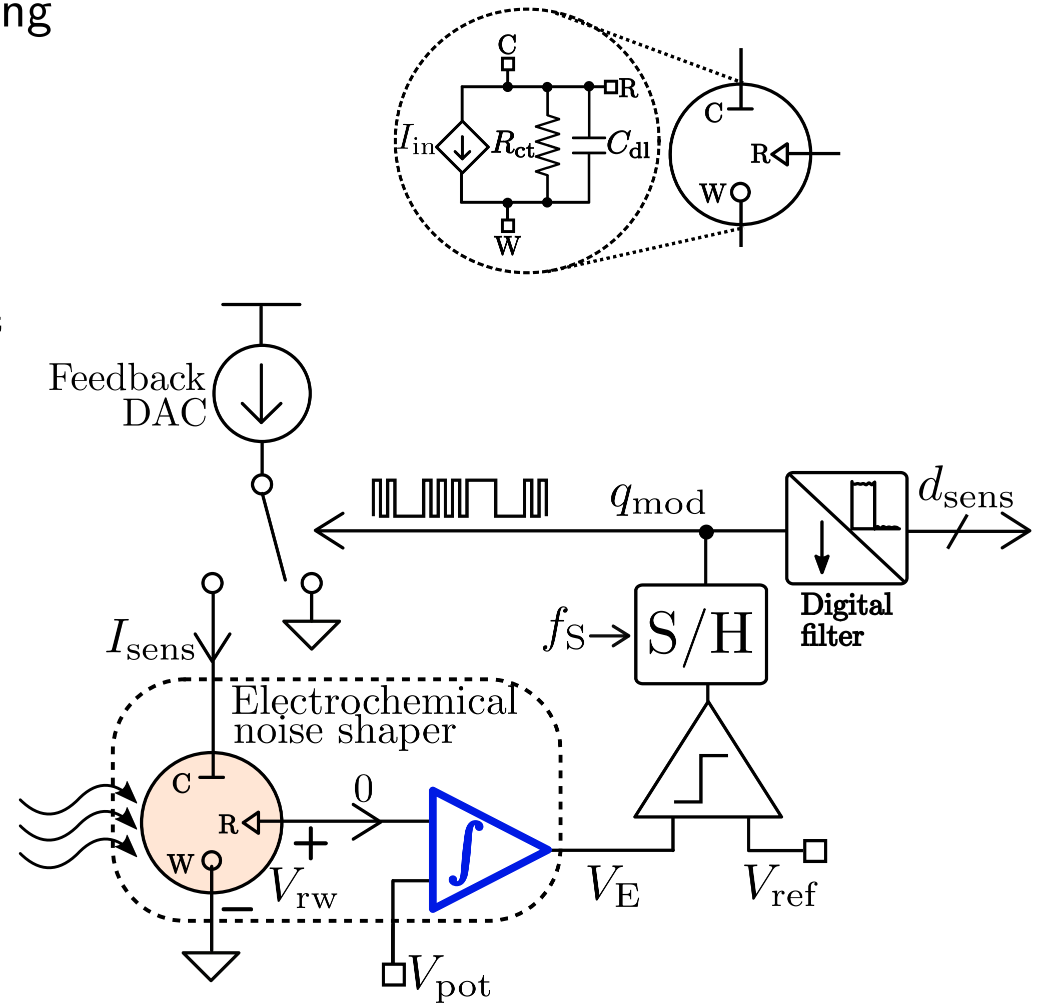






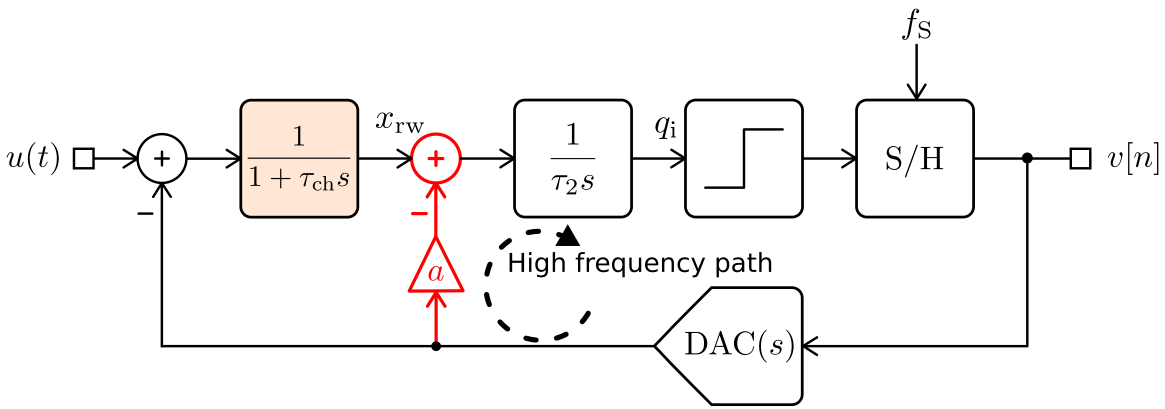
Proposed amperometric potentiostatic ΣΔM

- Incremental work: Addition of **electronic integration**
- **Higher resolution:** 2nd order noise shaping
- **Idle tones** attenuation
- **Potentiostatic operation** well-defined
  - Electronic integrator forces $V_{\mathbf{rw}} = V_{\mathbf{pot}}$
- New design trade-offs!
  - **Stability compensation** is required
  - A **zero** must be added in the **loop filter** to compensate the phase shift



Stability compensation

▶ Distributed FeedBack Topology

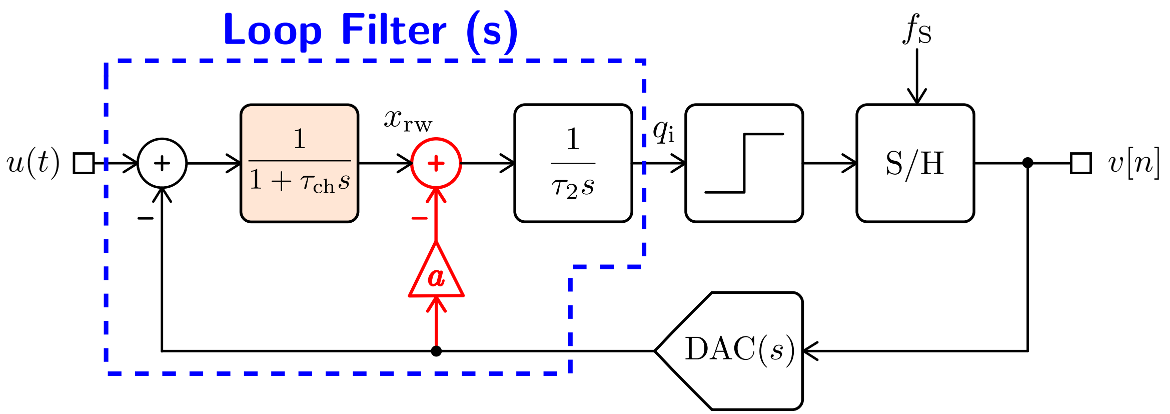


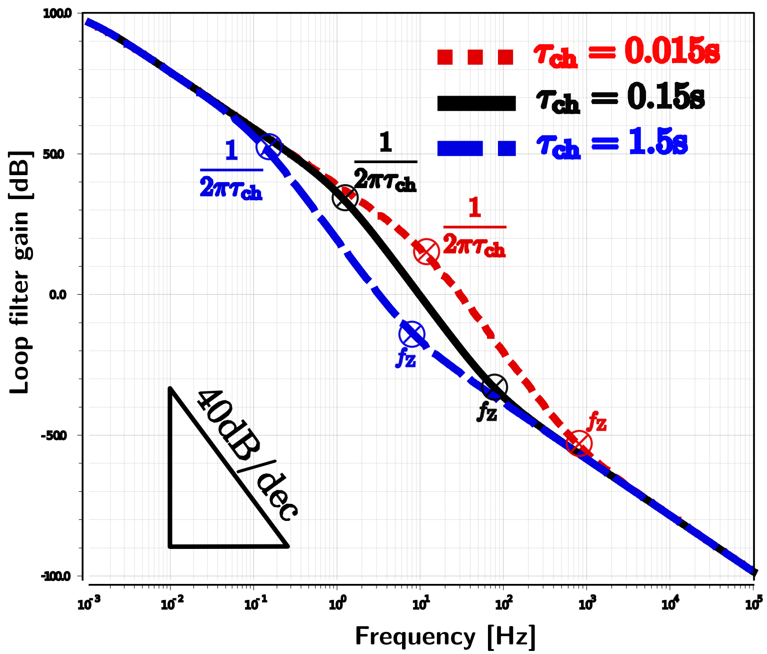
▶ **Loop Filter Zero** frequency **location**

$$H_{FB}(s) \approx \frac{1 + \frac{a}{1+a}\tau_{ch}s}{(1+\tau_{ch}s)\tau_2 s} \quad ; \quad f_Z = \frac{1+a}{2\pi a \tau_{ch}}$$

Stability compensation

- **Distributed FeedBack Topology**





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- **f_Z depends** on sensor time constant τ_{ch}
  - $\downarrow\tau_{ch} \rightarrow \uparrow f_Z$ **Leading to instability!!**

Stability compensation

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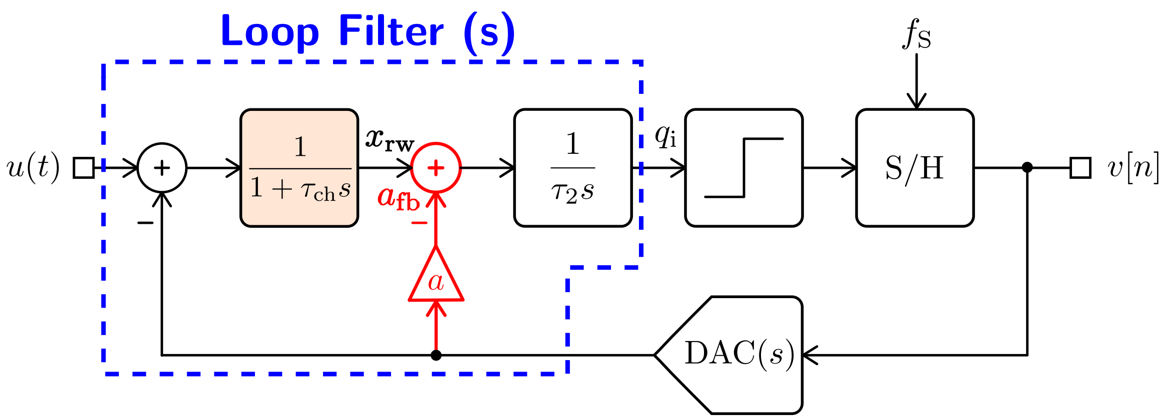

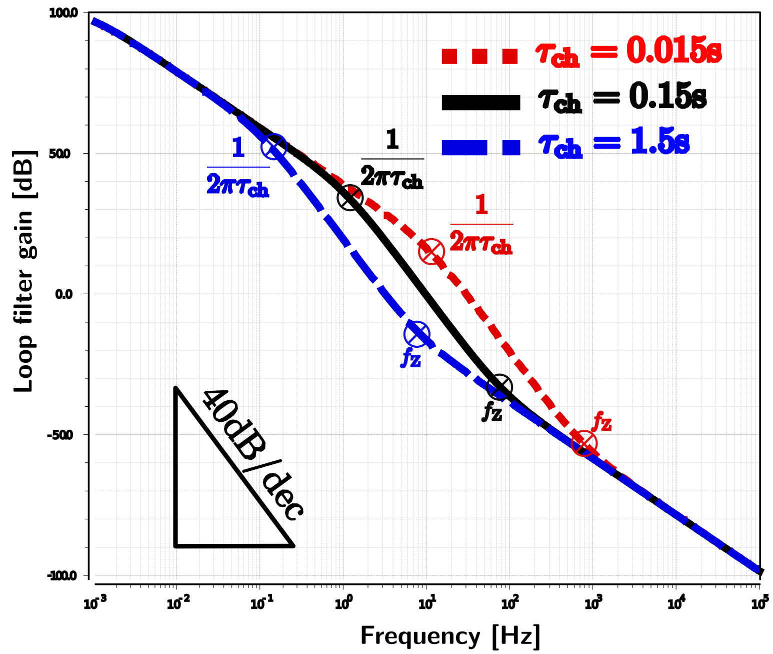

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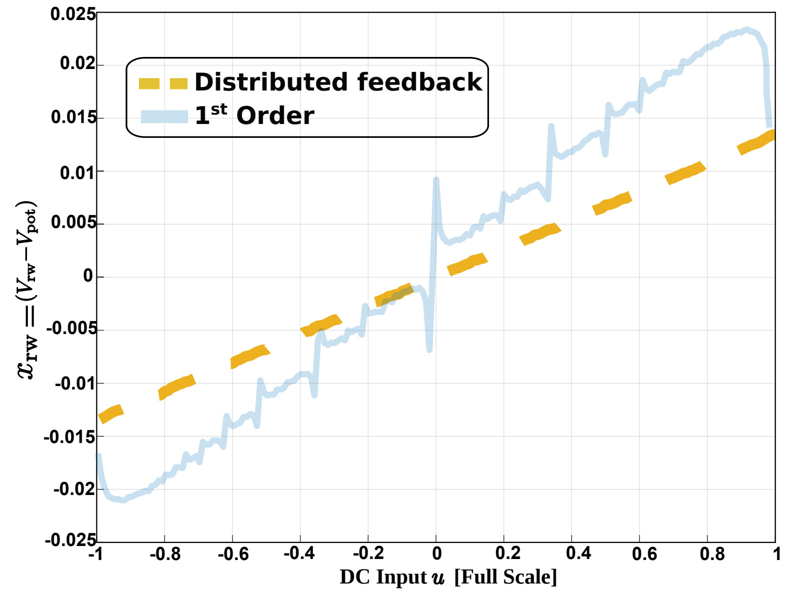
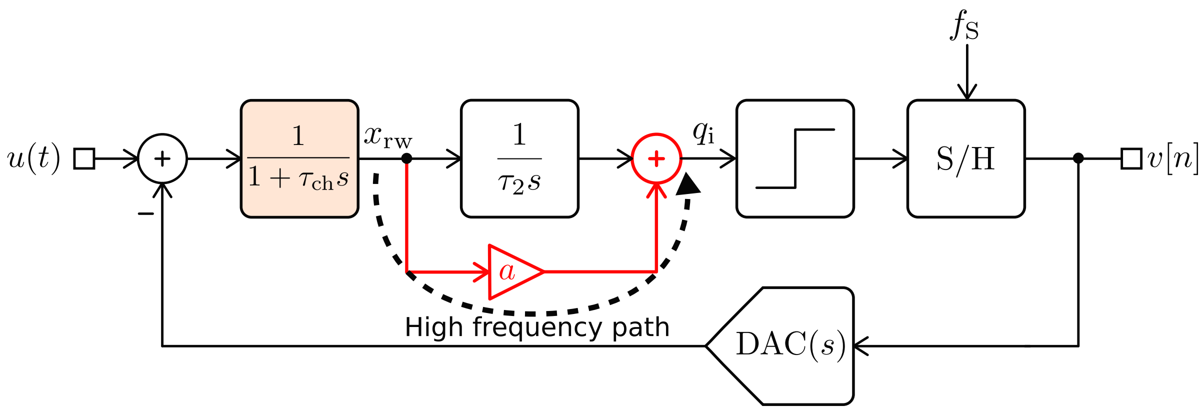
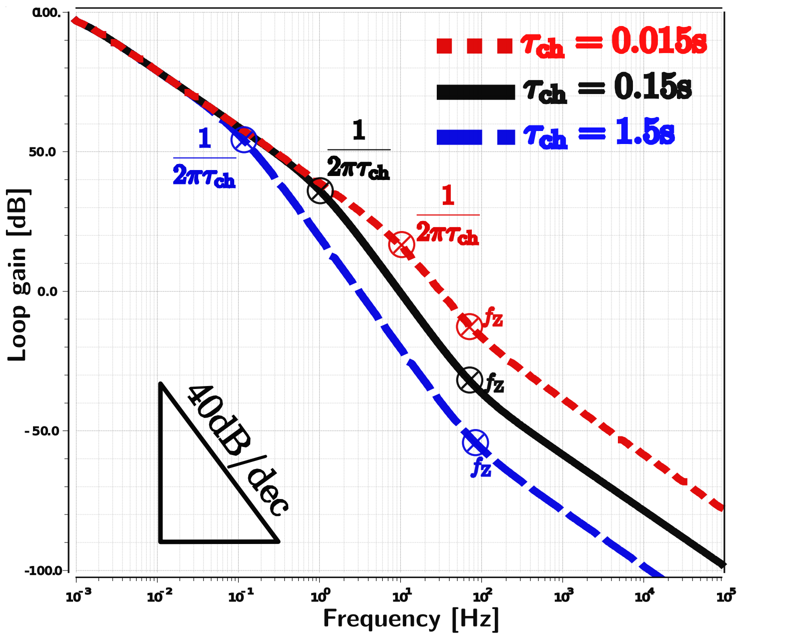
- **f_Z depends** on sensor time constant τ_{ch}
  - $\downarrow \tau_{ch} \rightarrow \uparrow f_Z$ **Leading to unstability!!**
- **Potentiostatic** voltage strongly **influenced** by the **sensor input signal**
  - $x_{rw} = a_{fb}$



Stability compensation

- **Feed-Forward Topology**





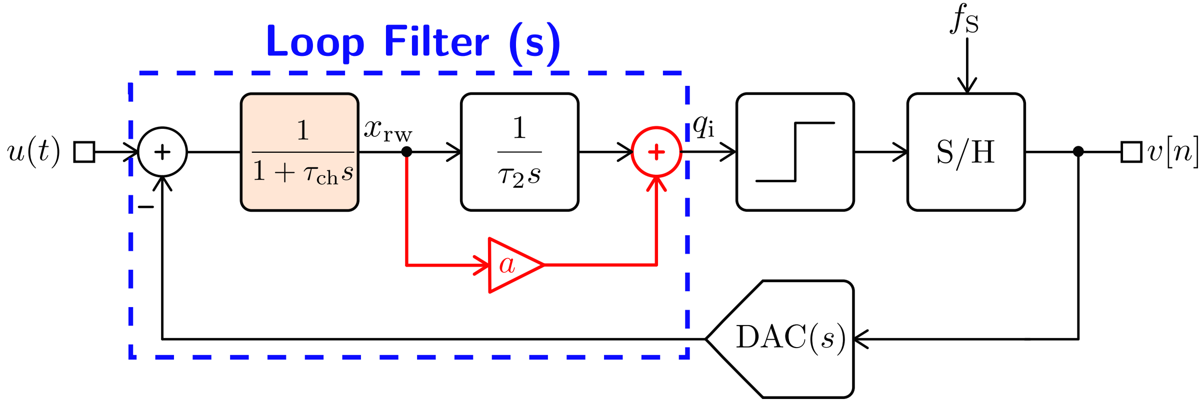
- **Loop Filter Zero** frequency **location**

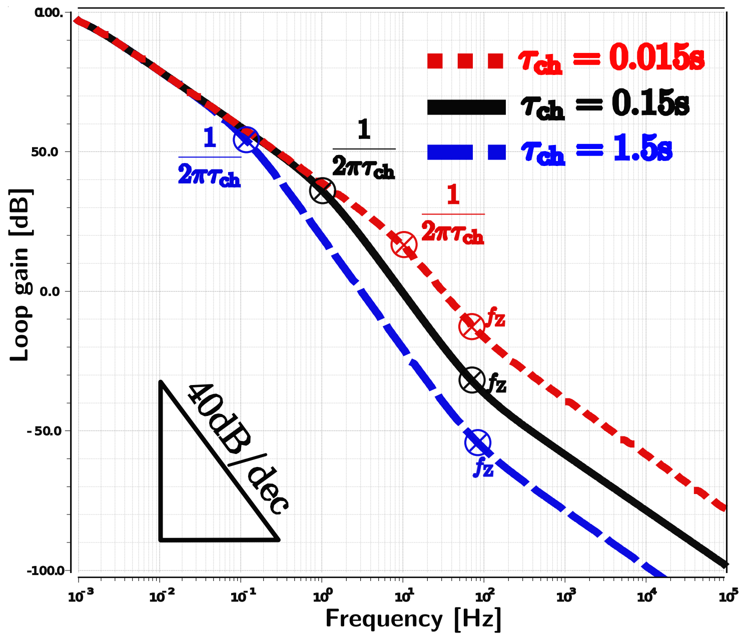
$$H_{FF}(s) = \frac{1 + a\tau_2 s}{(1 + \tau_{ch}\, s)\tau_2 s} \; ; \quad \boxed{f_Z = \frac{1}{2\pi a \tau_2}}$$

- Variations in the sensor time constant do not compromise the stability of the system!

Stability compensation

- **Feed-Forward Topology**





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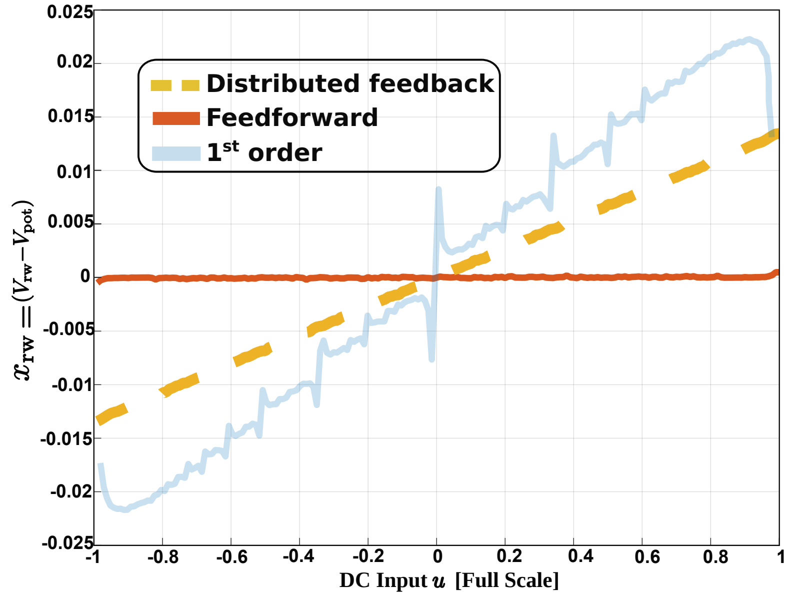
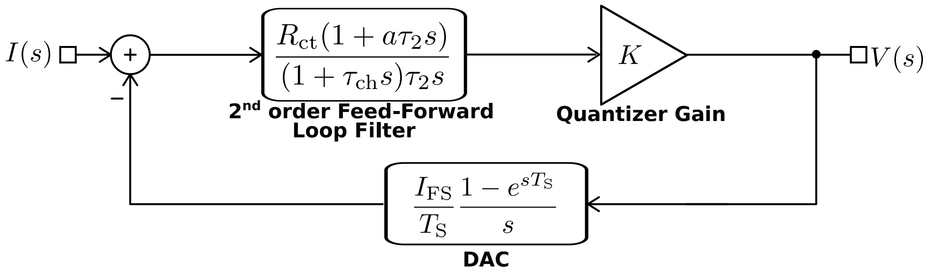
  - **Variations in the sensor** time constant do not compromise the stability of the system!

- **Electronic integrator forces** its input x_{rw} to have **DC zero component**.

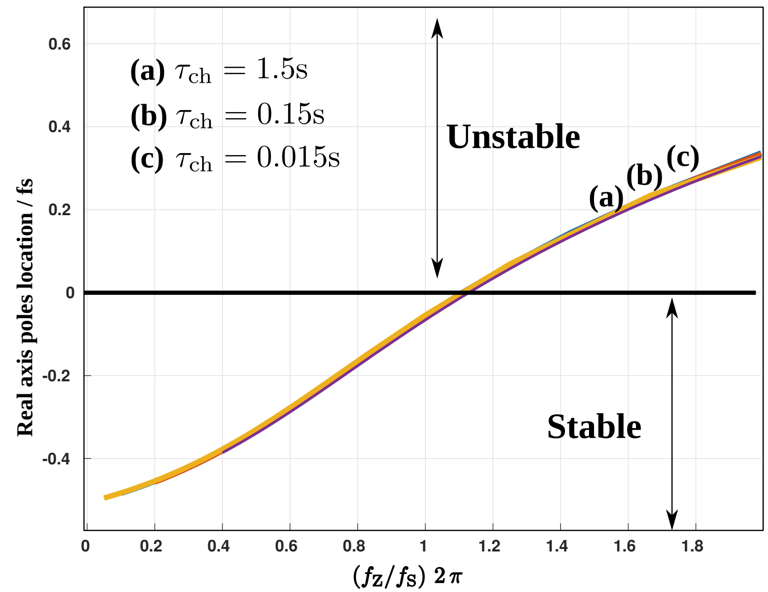


Small-Signal Stability Analysis

- **Linear model**



Linear model



- **Stability region as a function of f_Z/f_S**
  - **Root locus** analysis: Closed-loop poles moves as quantizer gain changes
  - **Stability condition:** $f_Z < f_S/(2\pi)$

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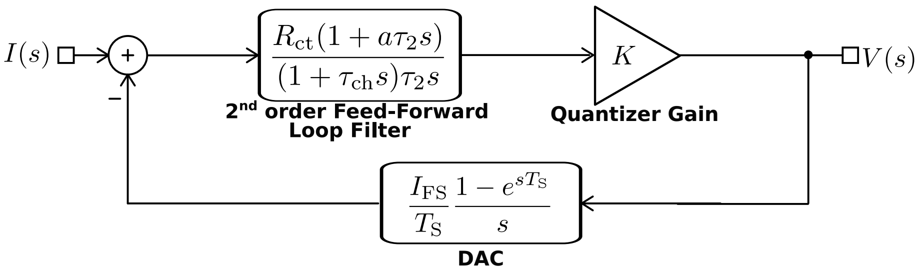

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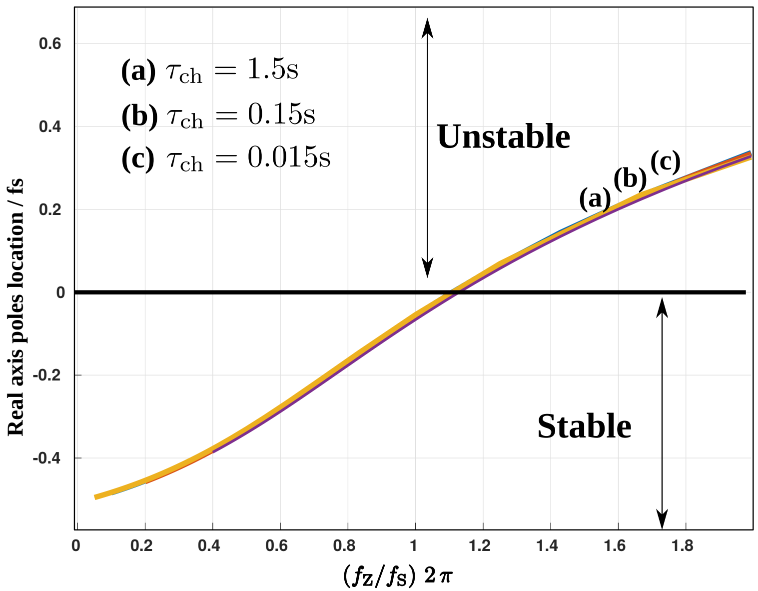

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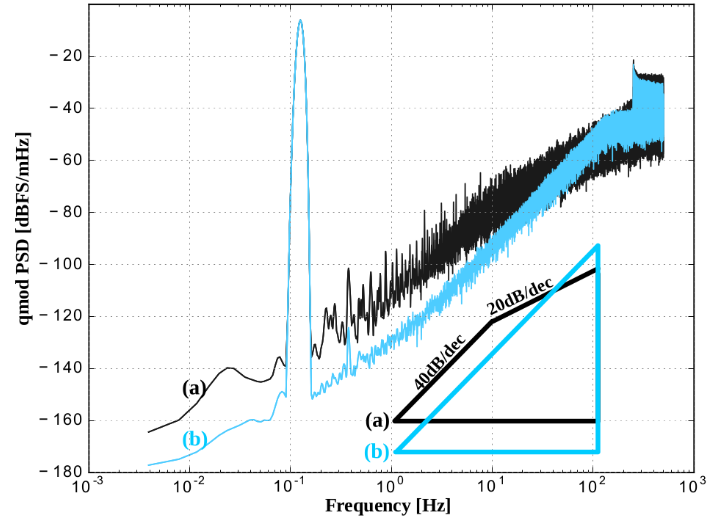
- **Power Spectrum as function of zero location**



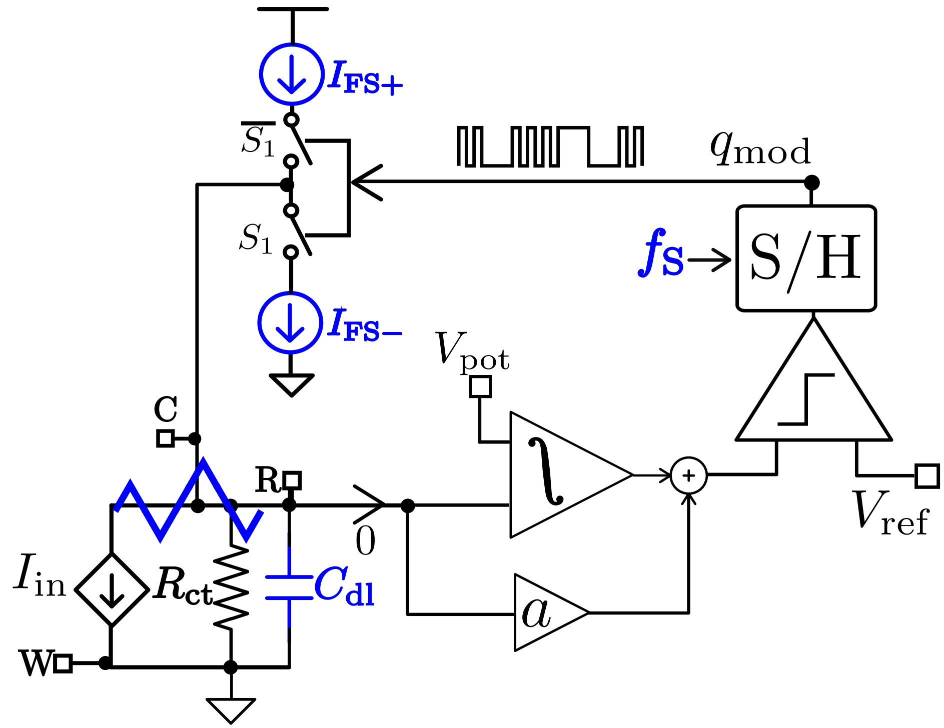
More stable (More 1st order behaviour)
Less aggressive **noise shaping**

Less safety **stability margin**
Better noise shaping

Potentiostat Voltage Ripple

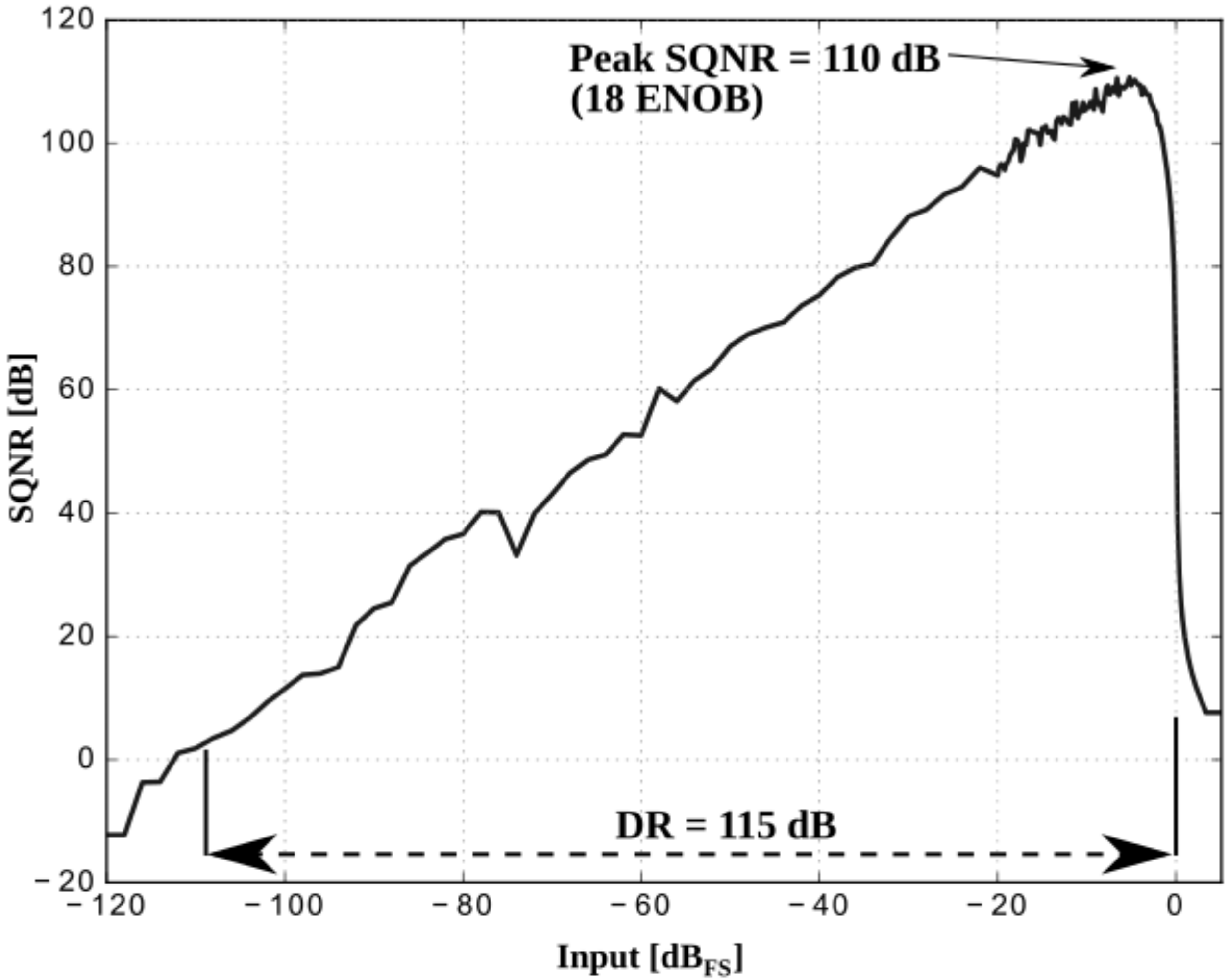
- Voltage ripple may be required to be kept below certain minimum
- Feedback current DAC (I_{FS}) **charges/discharges Cdl**
- $\mathbf{T_S}$ is the only degree of freedom to **minimize ripple**
  - ($\mathbf{C_{dl}}$ and $\mathbf{I_{FS}}$ are fixed by the application)

$$\frac{\Delta V_{\mathrm{rw}}}{V_{\mathrm{rw}}} \propto \frac{I_{\mathrm{FS}} T_S / C_{\mathrm{dl}}}{I_{\mathrm{FS}} R_{\mathrm{ct}}} = \frac{T_{\mathrm{S}}}{\tau_1}$$



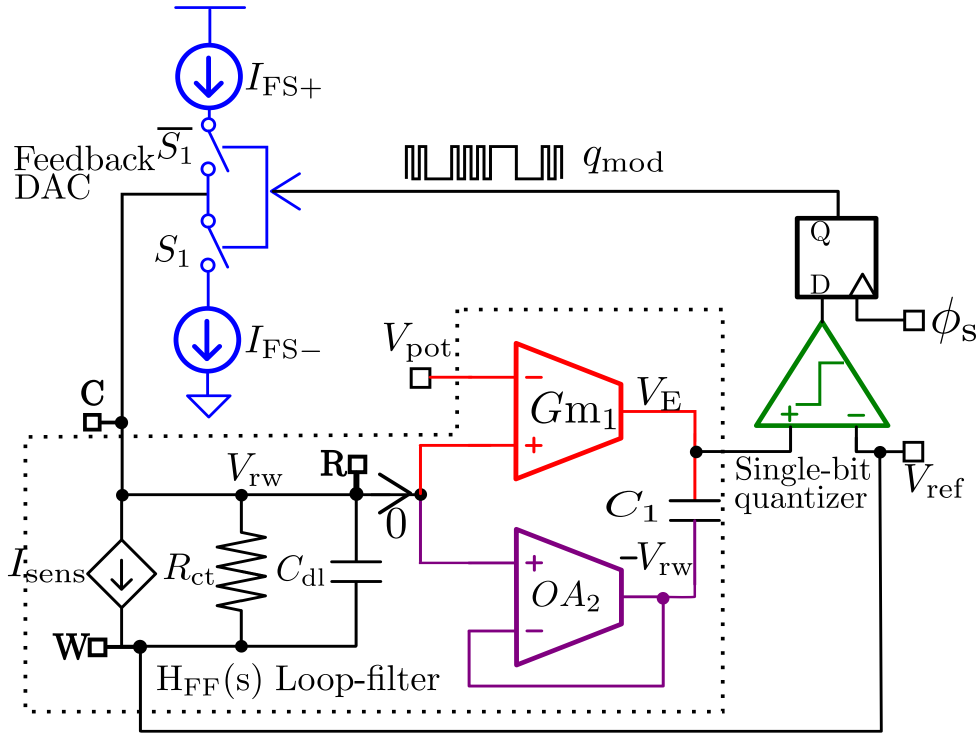
SQNR vs input signal

- **Top-level simulation**
  - $f_S = 1k\text{Hz}$
  - $\tau_{\text{ch}} = 0.15\text{s}(OSR \approx 500)$
  - $f_Z/f_S = 1/(4\pi)$
  - $I_{\text{FS}} = 2\mu A$



Low-power circuit implementation

- **Flexible** and **modular** to be mapped into different CMOS technologies
- **Electronic integrator: Gm_1-C_1**
- **Feed-Forward path**
- **Latch comparator** for 1-bit quantization
- **D-type flip-flop** for S/H
- **Feedback current DAC**
  - Power consumption mainly determined by current DAC FS, allowing chemical reaction take place

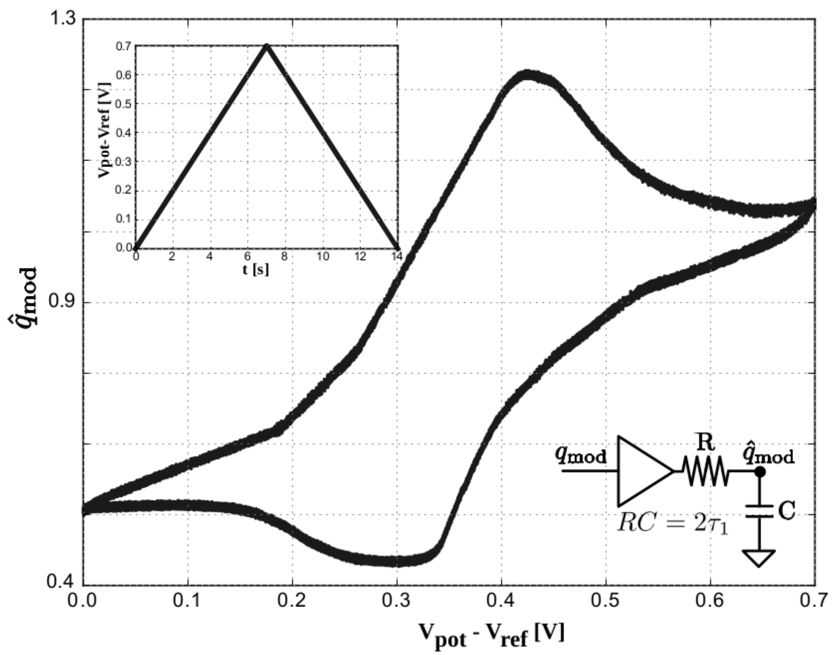


Simulation Results

- **Performance simulation results**
  - Power consumption mainly determined by current DAC FS
    $P_{DAC} = 4.7\mu W$
  - Rest of circuit blocks
    $P = 370nW$
- **Cyclic Voltammetry**
  - Method for studying electrochemical reactions
  - Triangular waveform is applied to the **R**eference-electrode, while the sensor current is measured simultaneously.
  - **VerilogA** model

0.18μm CMOS technology

Parameter	Symbol	Value	Unit
Supply voltage	V_{DD}	1.8	V
Potential range	$V_{pot} - V_{ref}$	± 0.7	V
Input full scale	I_{FS}	± 2	μA
Oversampling ratio	OSR	500	–
Sampling frequency	f_S	1	kHz
Loop-filer zero location	f_Z/f_S	$1/\pi$	–
Potentiostatic ripple	ΔV_{rw}	11.6	mVrms
Power at $2\mu A_{FS}$	P_D	5.1	μW



Ferrocyanide Cyclic Voltammetry

Conclusions

- **Compact architecture** thanks to the electrode-electrolyte interface used as an integrator stage in the $\Delta\Sigma$ structure
- **Minimalist** analog circuits fully integrable in purely digital CMOS technologies
- **High resolution** with kHz-range clock frequencies: $\mathrm{SQNR} = 110\mathrm{dB}\,@\,1k\mathrm{Hz}$
- **Ultra low-power ($370n\mathrm{W}$)** operation compared to sensor consumption

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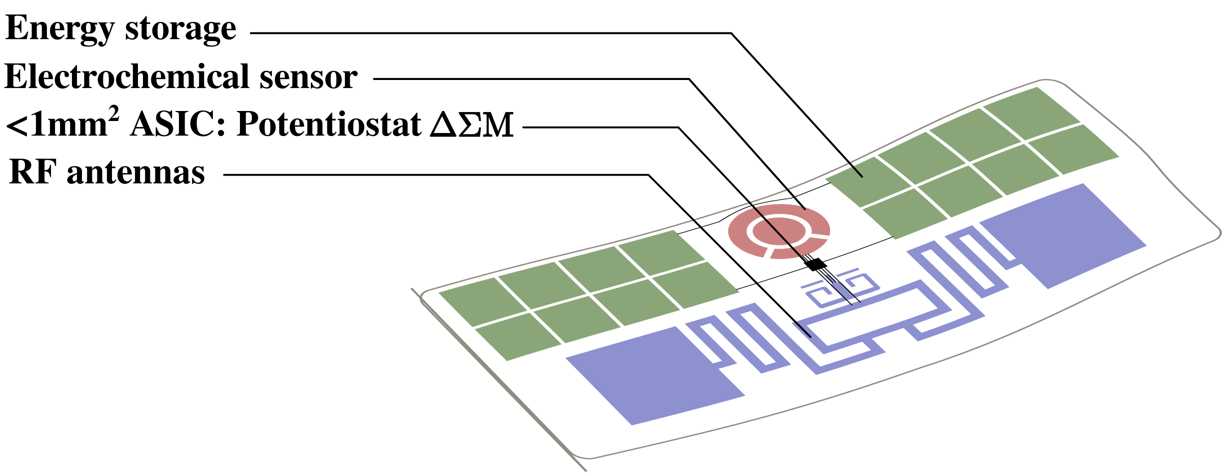
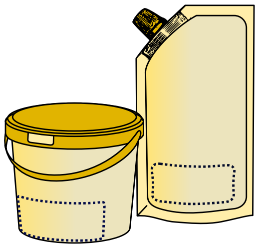
Future work





Smart tags for food quality control

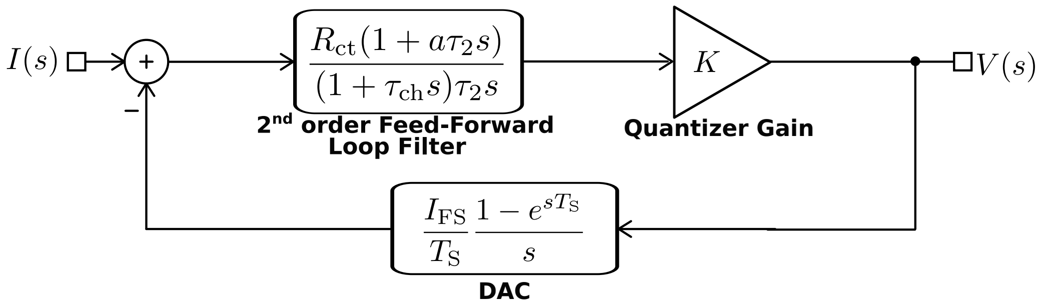
Wireless contact lens for health monitoring

Power Consumption Comparison

						[This work]
Technology	0.18 µm	0.5 µm	0.13 µm	0.18 µm	2.5 µm	0.18 µm
ADC structure	Current to frequency	Delta-sigma	Single-Slope	Delta-sigma	Delta-sigma	Delta-sigma
Sampling frequency	-	100 kHz	1.25 kHz	-	1 kHz	1 kHz
FS current	**150 nA**	**16 µA**	**600 nA**	**1.65 µA**	**2 µA**	**2 µA**
Power consumption	**3 µW**	**241 µW**	**56 µW**	**920 µW**	**25 µW**	**5 µW**
@ supply voltage	@ 1.2 V	@ 1.2 V	@ 2 V	@ 1.8 V	@ 5 V	@ 1.8 V

Small-Signal Stability Analysis

- **Linear model**



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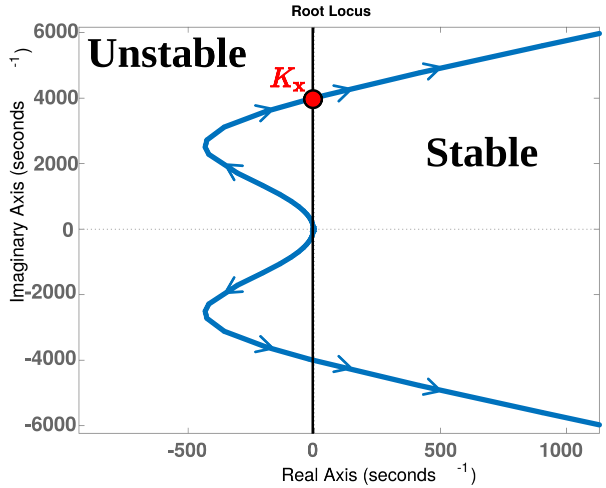

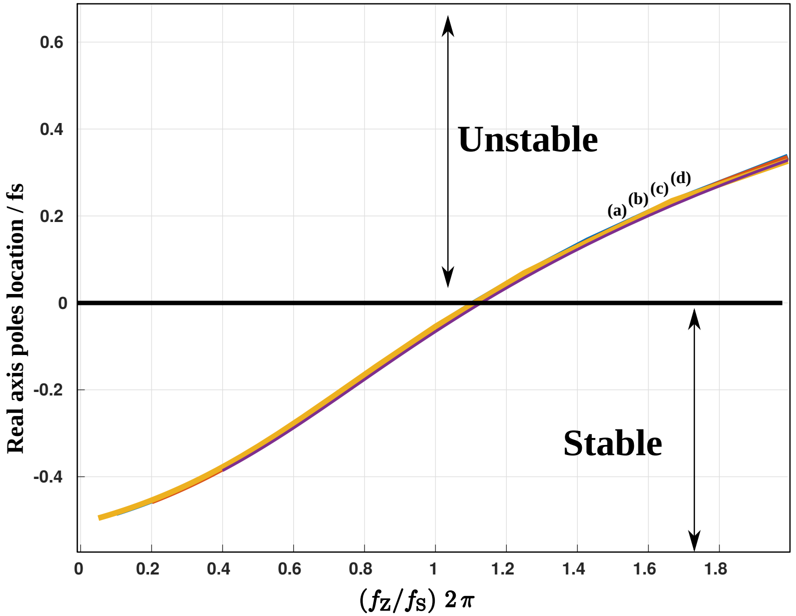

- **Root Locus**
  - Stability region as a function of **K**
  - Worst-case scenario when K is maximum
- **From stable situation**
  - Sweep input: 0 to FS to find maximum quantizer gain Kmax (worst-case)
- **Stability region as a function of f_Z/f_S**
  - Sweep f_S/f_Z and check if Kmax is within the stable region
- **Stability is ensured if:**

$$\frac{f_Z}{f_S} < \frac{1}{2\pi}$$