Sensors and Actuators

Measurement system structure

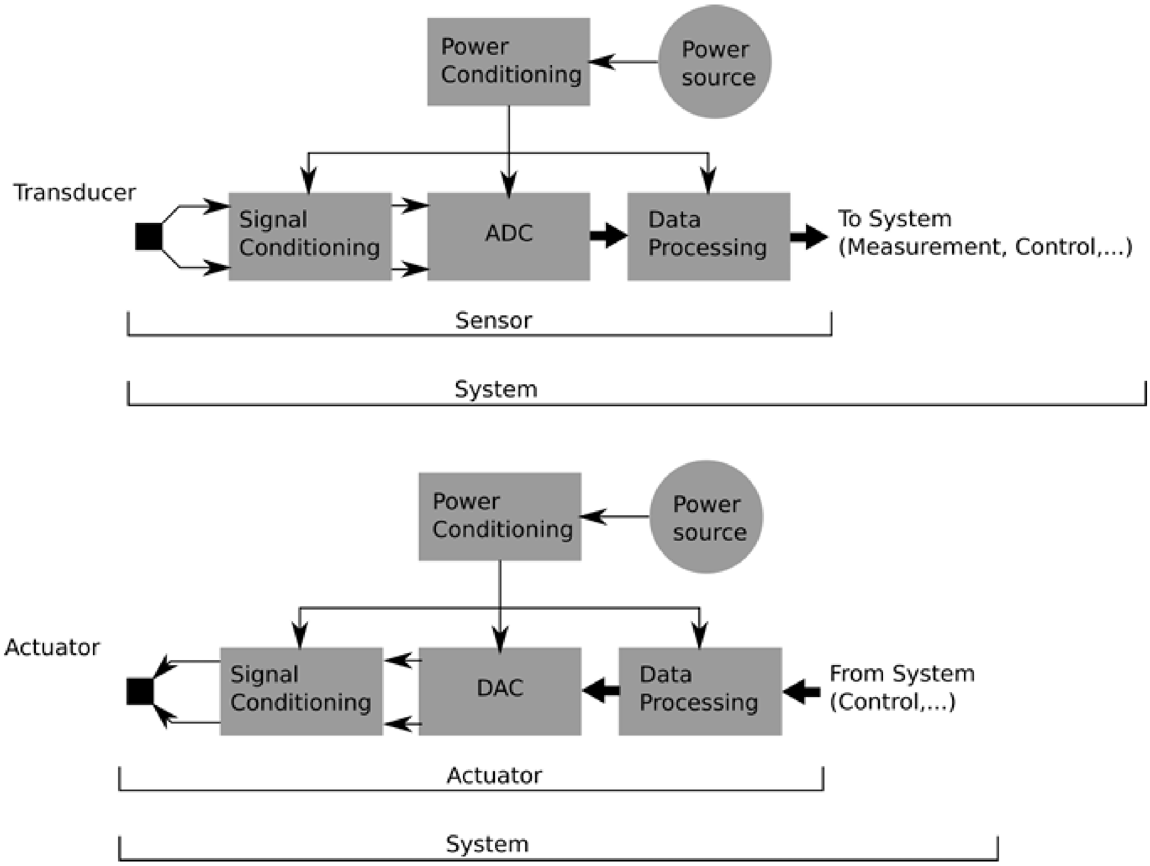


Figure 1.1.: Measurement/Actuator System Structure

Table 1.1.: Relevant Sensor System Parameters

Transducer	**Sig. Conditioning**	**ADC**	**Data process.**	**Power**
Range	Range	Range	Range	Range
Nominal Value	Nominal Value	Nominal Value	Nominal Value	Nominal Value
Resolution (?)	-	Resolution	-	-
Sensitivity	Sensitivity	Sensitivity	-	-
Accuracy	-	Accuracy	-	Accuracy
Linearity/Gain	Linearity/Gain	Linearity/Gain	-	-
Offset	Offset	Offset	-	Offset
Temp. Stability	Temp. Stability	Temp. Stability	-	Temp. Stability
Bandwidth/Slew rate	Bandwidth/Slew rate	Sample Freq	Transfer rate	-
Noise	Noise	Noise	Noise	Noise/Ripple
Repeatability	Repeatability	Repeatability	-	Repeatability
-	CMRR/PSRR	CMRR/PSRR	-	-

Range:

Physical boundary conditions of the sensor.

Nominal Value:

The Area in which the sensor values are the most accurate.

Sensitivity:

The ratio of change in the output to the change in input.

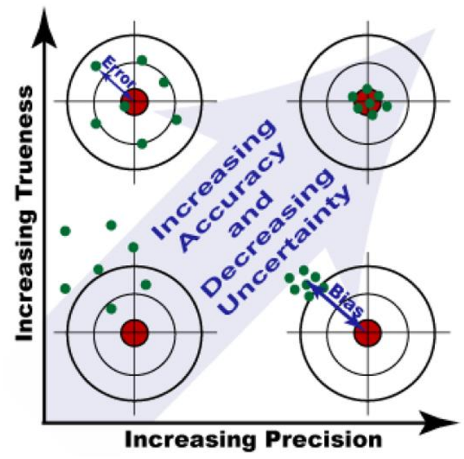
S= output value / input value

Accuracy:

The Accuracy describes how close the sensor values are to the actual values.

Precision:

Precision is how close the measurement results are to each other.



Repeatability:

Getting consistent measurement results in the same environment.

Reproducibility:

The ability to get the same results in a changing environment/ varying conditions.

Uncertainty:

It reflects the doubt about the exactness of a measurement.

Often Accuracy can be viewed as the degree of uncertainty. Therefore, often quantitative values are assigned to accuracy.

Type A from statics

Type B from datasheet

Stability:

Can be divided into long and short term stability.

Short term stability evaluates the performance over a brief period of time.

Long term stability evaluates the performance over a prolonged period of time.

Environmental factors, their changes and the aging of the sensor have an impact on stability. This is why regular maintenance and calibration is needed.

Bandwidth:

Dynamic Characteristics of the physical system:

The bandwidth must be able to accommodate all relevant metrics of the system. For instance for a fast changing system a higher bandwidth is needed.

Statistical operations of measured quantities:

Often oversampling has to be used for anti aliasing . This improves signal to noise ratio and the post processing results.

Signal integrity and Noise

Data Acquisition system capabilities:

Regarding processing speed, data storages capacity and access methods

Control System Dynamics:

Bandwidth has direct influence on accuracy and stability.

Application Specific Requirements:

It depends.

Common mode rejection ratio CMRR:

Describes how good the OPAMP can get rid of the common voltage (direct current) of a signal. This means if on the two inputs of a OPAMP would be the same noise, it would be possible to get rid of this noise. This would not be necessary if the common mode gain Acm would be zero.

Power supply rejection ratio PSRR:

Describes how much the noise in the supplied power for an OPAMP is damped/ visible at the output.

Error Budget:

In general, the standard deviation is used for uncertainties in the error budget.

$$u_c(y) = \sqrt{\sum_{i=1}^{N} c_i^2 u^2(x_i)} = \sqrt{\sum_{i=1}^{N} u_i^2(y)}$$

U refferes to the error of each individual component

Transducers

Transducers are the interface from the physical into the electronical world. The convert physical quantities in electrical signals.

- Inductive transducers: Variations in inductance
- Capacitive transducers: change in capacity
- Magnetic Transducers: Detect changes in magnetic field
- Resistive Transducers
- Piezo electric transducers
- optical transducers

Resistive Transducers:

The resistivity is changed by changing one of those three parameters:

- Geometry: cross section change
- Temperature
- Magnetic field

Eg: strain gauges

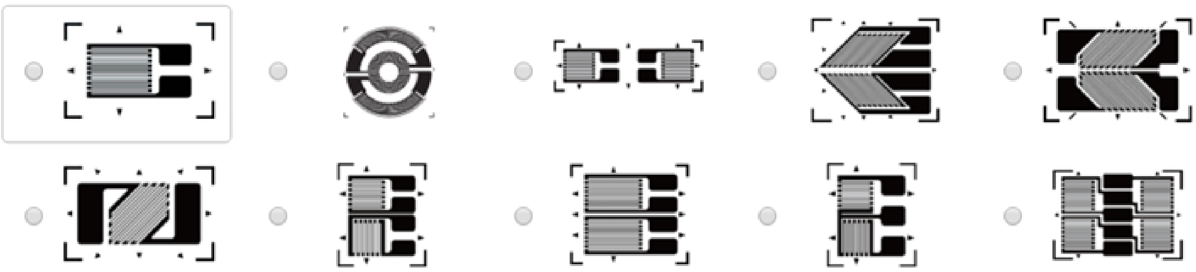


Figure 2.1.: Various Strain Gauge Types

Thermocouples:

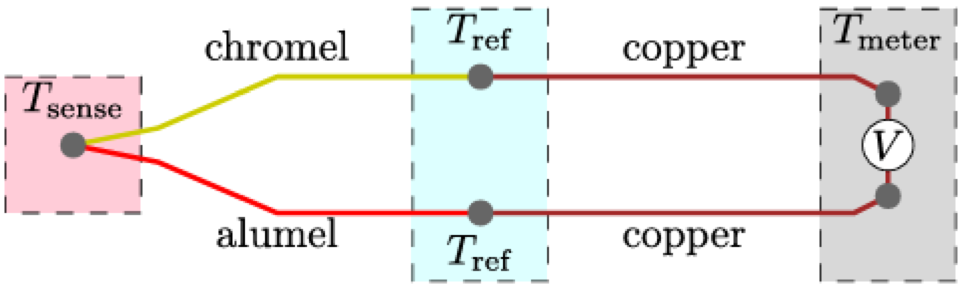


Figure 2.3.: K-type thermocouple principle

A thermocouple uses the seebeck effect. This effect states when that when two dissimilar materials are joined together at their ends to form a closed circuit, there will be an electromotive force (EMF) will be present in the junction. The generated voltage is proportional to the temperature difference in Tsense and Tref.

For the cold junction compensation Tref has to be measured by another sensor.

Piezoelectric Transducers:

The displacement of the crystalline structure causes a charge and vice versa. This does not work for static displacements. And is used for acceleration, forces etc.

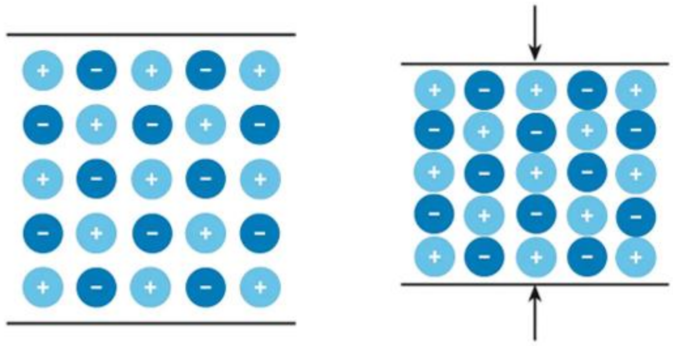


Figure 2.5.: Piezoelectric Effect [29]

Optical Transducers:

Optical transducers use the photo electric effect. Light (or better radiation) energy is absorbed by a material, causing the emission of electrons and creating an electrical signal. If you know CCD and CMOS from digital image processing u know.

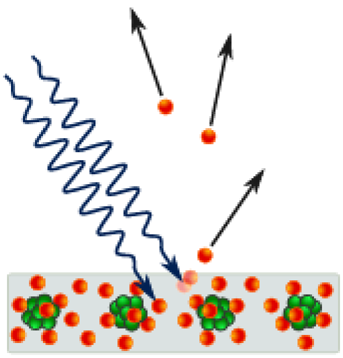


Figure 2.7.: Photoelectric Effect

Triangulation Sensor:

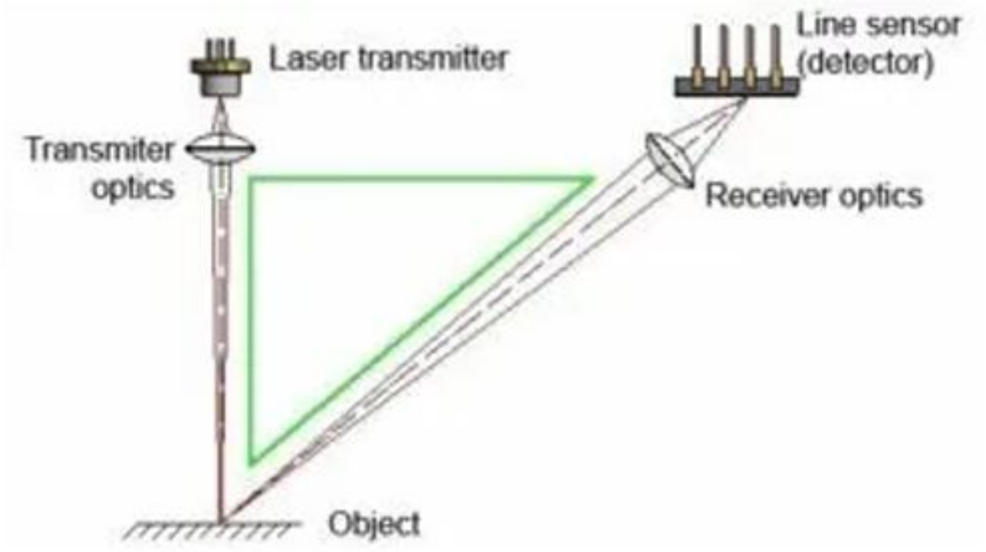


Figure 2.8.: Principle Laser Triangulation [31]

- Contactless
- High precision
- Sampling rate ?

Signal Conditioning

It refers to the manipulation of the raw signals from transducers. They are used to produce cleaner, reliable and meaningful data. It can enhance signal quality, suppresses noise and convert signals into other formats.

The quality of the conditioning affects accuracy, stability and reliability of the measurement system.

Design of the conditioning stages:

- Transducer Type: produce different signal types, methods need to accommodate their electrical characteristics
- Signal strength: may require amplification
- Noise environment
- Target application: different requirements
- Power consumption: consider power budget

Signal conditioning stages have several functions:

- Amplification: reduces signal to noise ratio
- Filtering
- ADC
    - Successive approximation register
    - Sigma delta ADC
    - Flash ADC
- Attenuation: reduces signal to a suitable level do not get into saturation
- Offset compensation gets DC-offset of the signal to a suitable level
- Linearization: used to correct non linear behavior of sensor
- Impedance matching: Maximize power transfer so measurement system receives signal without degradation

Filter

Low-Pass Filter

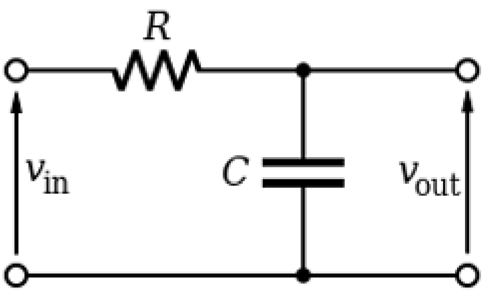


Figure 3.1.: RC Low-pass filter

$$H_{LP}(i\omega) = \frac{1}{1 + i\omega RC} \qquad f_c = \frac{1}{2\pi RC}$$

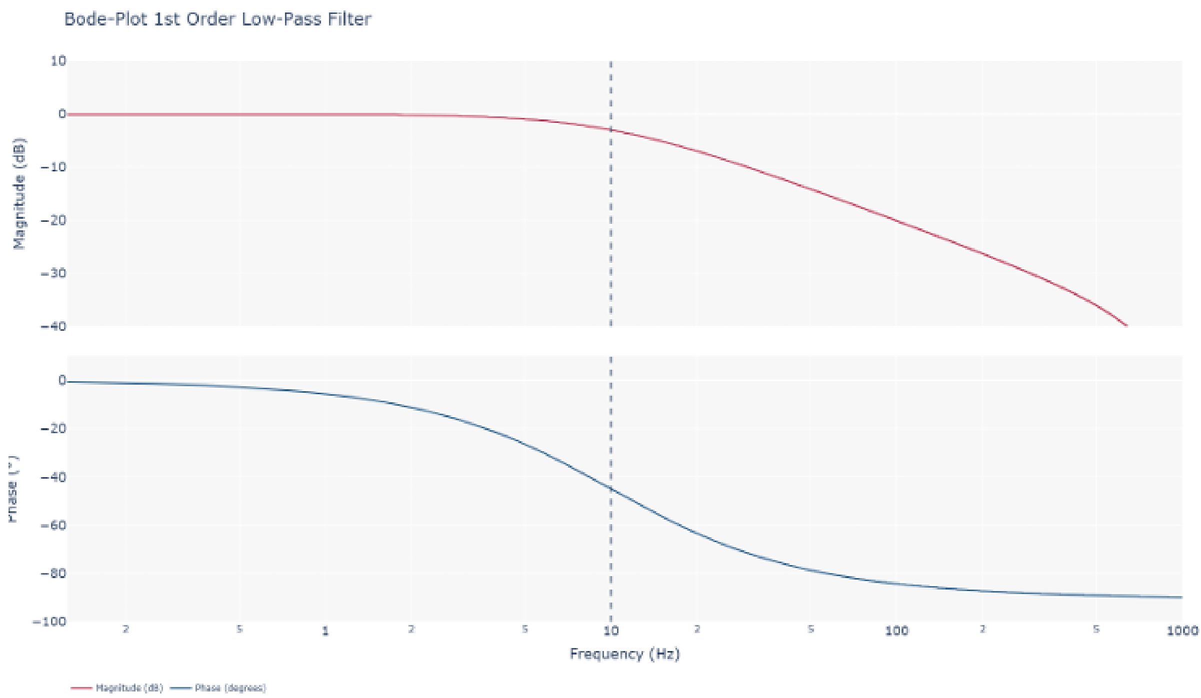
At fc the signal amplitude is reduced by -/3dB, this point is refferd to as the half power point.

The roll-off rate is a linear function of the filter order n. 20*n db/decade

$$\phi = -\arctan \omega RC$$

The phase response for a first oder RC-lowpass:

At fc the signal is shifted by 45°.



High-Pass Filter:

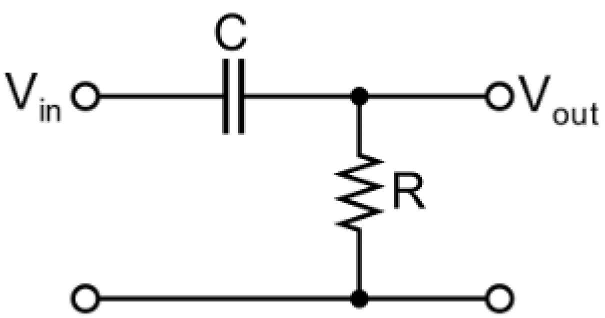


Figure 3.4.: RC High-pass filter

$$H_{HP}(s) = \frac{sRC}{1 + sRC} \qquad f_c = \frac{1}{2\pi RC}$$

Band Pass Filter:

Is a combination of high and low pass filter. It allows a specific range to pass.

$$H_{BP}(s) = \frac{s}{(s^2 + \frac{1}{Q}s + \omega_0^2)}$$

Q is the quality factor and describes the bandwith of the filter relative to the center of frequency.

Band-Stop Filter (Notch- Filter)

Frequencys of a specific range shall not pass. All others are allowed.

It could be discribed as the inverse of the band pass filter.

$$H_{BS}(s) = \frac{s^2 + \omega_0^2}{s^2 + \frac{1}{Q}s + \omega_0^2}$$

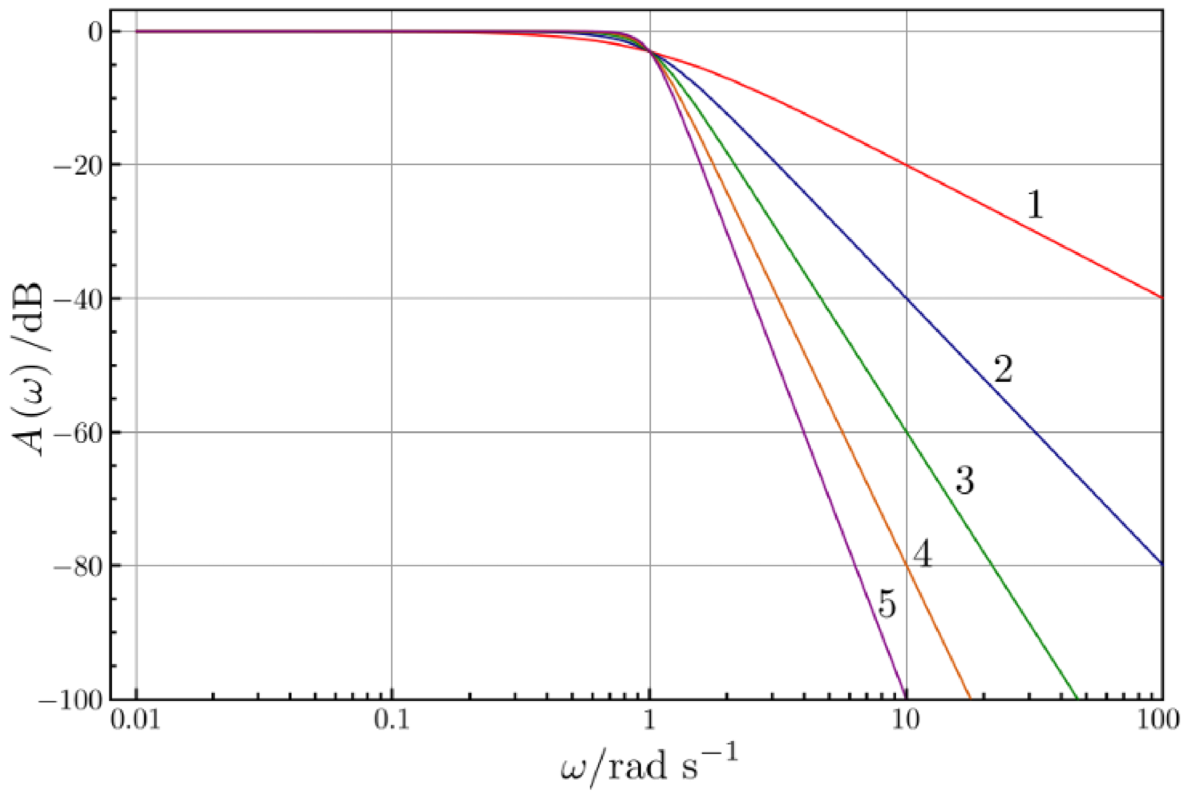
’s

$$H_{BS}(i\omega) = \frac{1 - i\omega RC}{1 + i\omega RC}$$

Is used to get rid of unwanted frequencies like eg. 50 Hz of the power supply.

Design Parameters:

- Cut off frequency
- Gain
- Roll-off
- Quality factor



Partical Consideration

The coiche of components influences the filter topology. Higher order filters require more components and are more complex to design. Lower order filters are simpler butt less precise in frequency discrimination.

Digital Filtering

$$y[n] = \sum_{k=0}^{M} b_k \cdot x[n-k] - \sum_{k=1}^{N} a_k \cdot y[n-k]$$

Finit Impulse Response (FIR) Filters

- Linear phase response
  - Preserves wave form
  - Good for problems that require phase accuracy

$$y[n] = \sum_{k=0}^{M} b_k \cdot x[n-k]$$

Windowing is the most common design methods for FIR filters.

Rectengular Window:

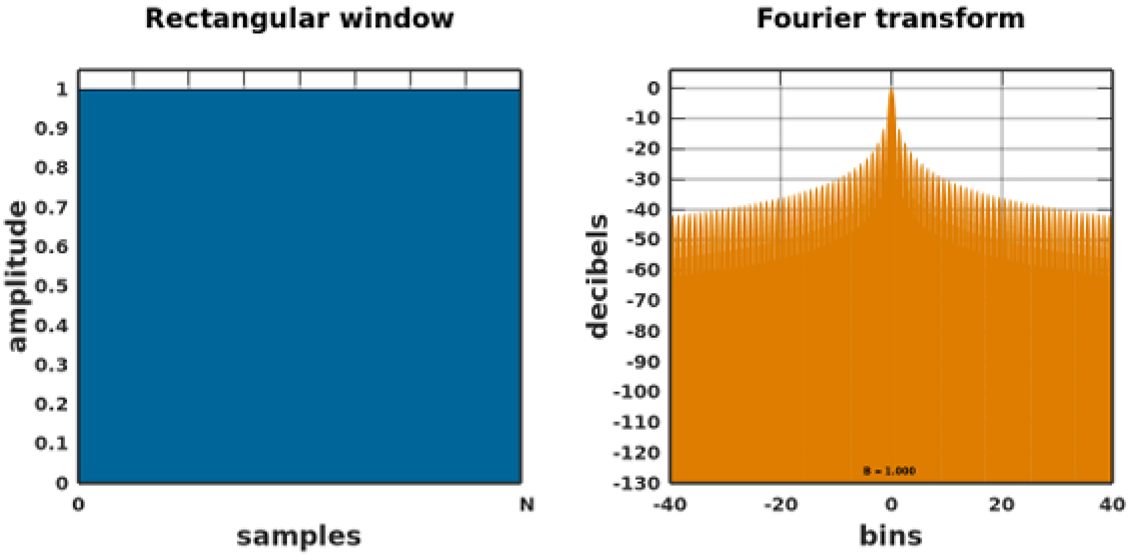


Figure 3.6.: FIR Rectangular Window

Hamming window

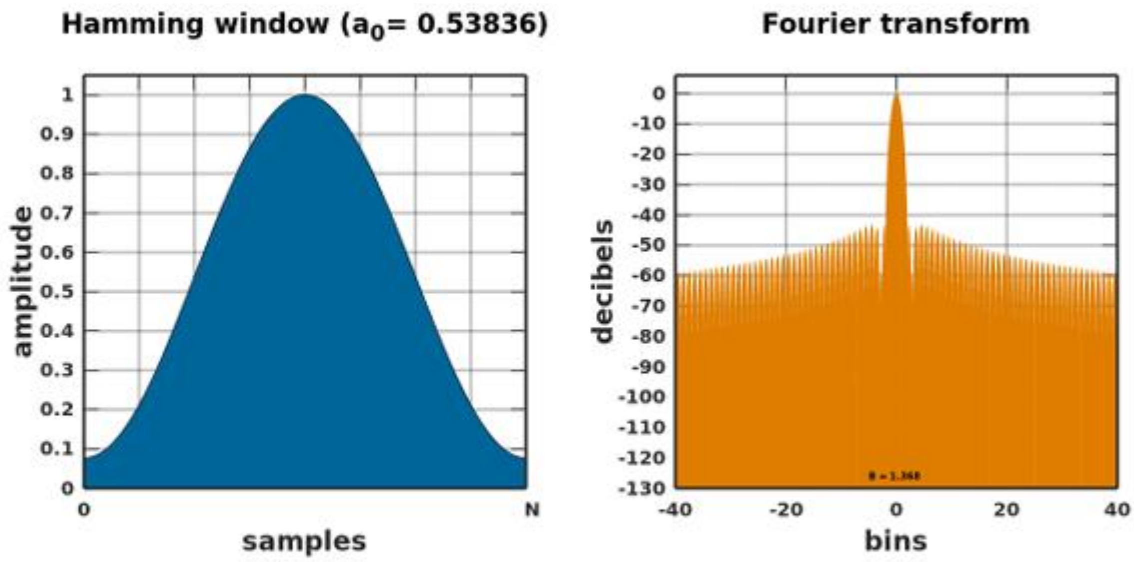


Figure 3.7.: FIR Hamming Window

Hanning window

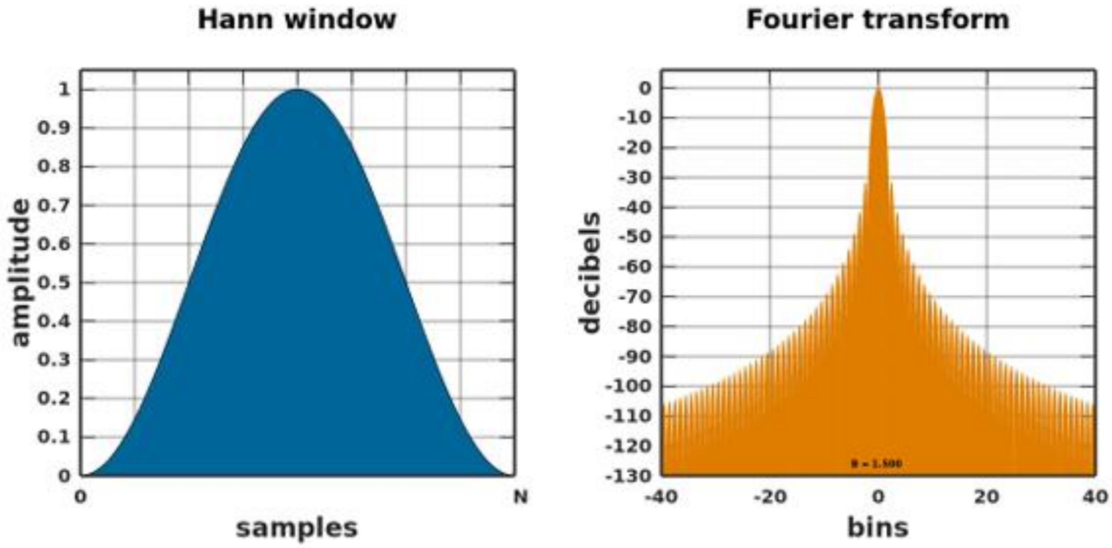


Figure 3.8.: FIR Hanning Window

Balckman Window

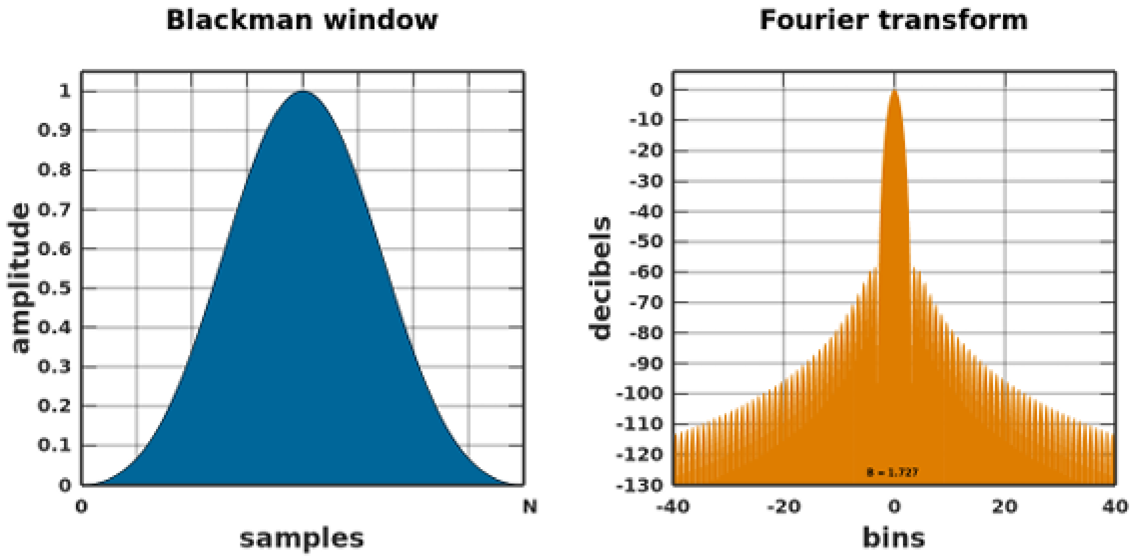


Figure 3.9.: FIR Blackman Window

Table 3.1.: Characteristics of Common Window Functions

Window	Main Lobe Width	Side Lobe Level (dB)	Typical Use
Rectangular	Narrowest	-13 dB	Applications with minimal stopband rejection needs
Hamming	Moderate	-42 dB	Balanced approach for moderate rejection
Hanning	Wider	-31 dB	Moderate side lobe suppression
Blackman	Widest	-58 dB	High side lobe suppression

Infinit impulse response (IIR) filters

Easy to calculate. It is an optimization problem.

- Use feedback
    - Can lead to instabilities
- Infinite duration impulse response
- Used for applications requiring computation and sharper cutoff characteristics

Typical types:

- Butterworth filter
- Chebyshev type 1 filter
- Chebyshev type 2 filter
- Bessel filter

Bilinear Transformation

Transformation used to get the transferfunction of real filters (that are in s domain) in a discrete domain (z-domain). Therefore the following substitution is used:

$$s = \frac{2}{T} \cdot \frac{1 - z^{-1}}{1 + z^{-1}}$$

- Stability of the system is preserved
- The frequency is shiftet by the transformation and needs to be corrected

Comparisson FIR and IIR

Table 3.2.: Comparison of FIR and IIR Filters

Aspect	FIR Filters	IIR Filters
Impulse Response	Finite (settles to zero after a finite time)	Infinite (decays gradually)
Phase Response	Can be designed for linear phase	Nonlinear phase
Stability	Always stable	Can be unstable if not designed carefully
Computational Efficiency	Higher order needed for sharp transitions	Achieves sharp transitions with lower order
Memory and Processing Needs	Generally higher	Lower due to fewer coefficients
Application in Real-Time	Often slower due to higher computation	Faster response with lower delay
Flexibility in Design	Can approximate any desired response	Limited flexibility in complex response design
Multirate Filtering	Well-suited for multirate applications	Less suited for downsampling/upsampling

In summary, FIR filters are preferred in applications requiring linear phase and guaranteed stability, while IIR filters are advantageous in applications where a compact design with fewer coefficients is prioritized-> less computational cost.

ADC

The process of the conversion consists of two steps:

- Sampling: sampling signal in regular intervals
- Quantization: Each sample is assigned to the nearest quantization level

The quality of an ADC is determined by:

- Resolution: bits

- Sampling rate
- Conversion time
- Dynamic range: ratio of maximum to minimum input
- Noise: level of noise introduced by ADC (quantization noise)

Sigma-Delta ADC

- Highly efficient conversion
    - Good for application with requiring high resolution and low frequency
- Idea for sensor based systems with low noise measurement required
- Oversample by a large factor-> spreading quantization noise

• Modulator Block

• Digital Signal Process Block

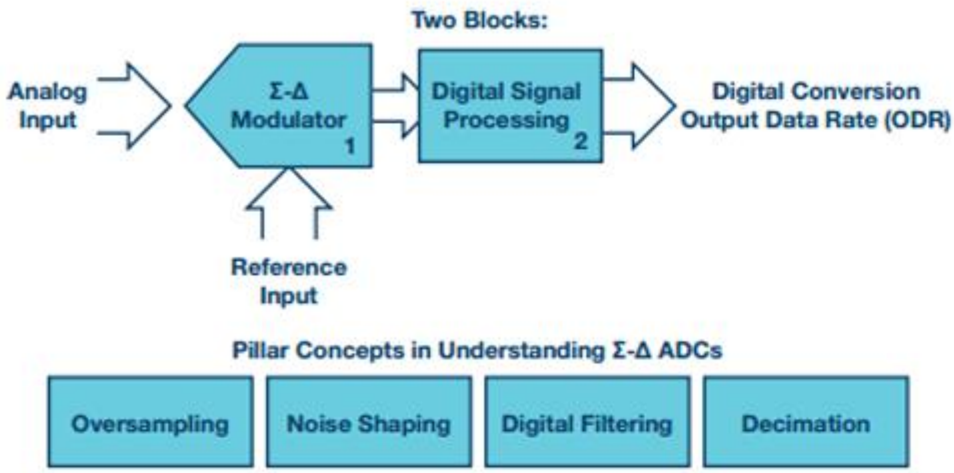


Figure 3.10.: Main concepts of $\Sigma\Delta$ ADC

Modulator Block produces a PWM signal

Quantization Noise

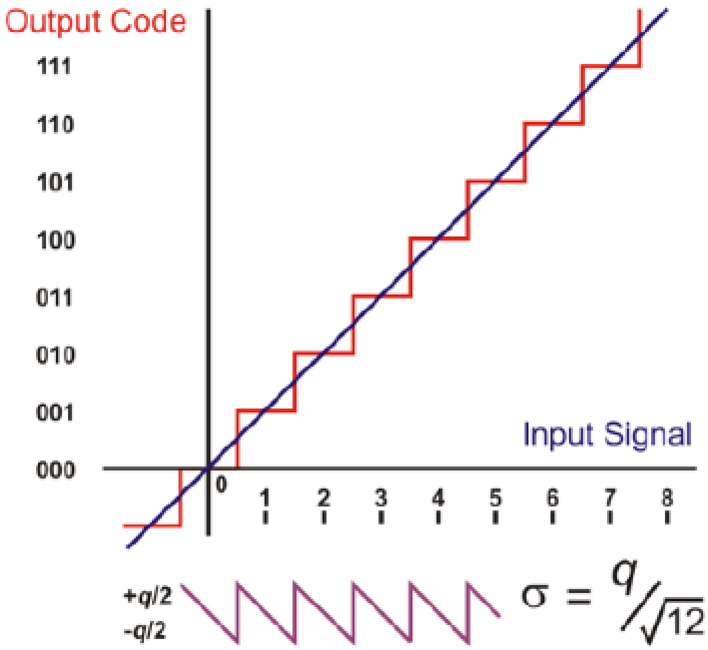


Figure 3.11.: ADC Quantization Error [33]

If a Signal is transformed to the digital domain, it is sorted into different values. I can not be know if the original value is on the high or low end of the quantization step. Therefore the error is of the of the value of 1LSB,

Delta-Sigma ADC use noise shaping techniques and push much of the quantization noise outside the signal band.

Signal to noise ratio

$$SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) = 10\log_{10}\left(\frac{{V_{fs}}^2}{\sigma^2}\right)$$

The effective number of bits ENOB describes how many bits are still usable, since the resolution degrades with higher noise.

$$\text{ENOB} = \frac{SNR - 1.76_{dB}}{6.02_{dB}}$$

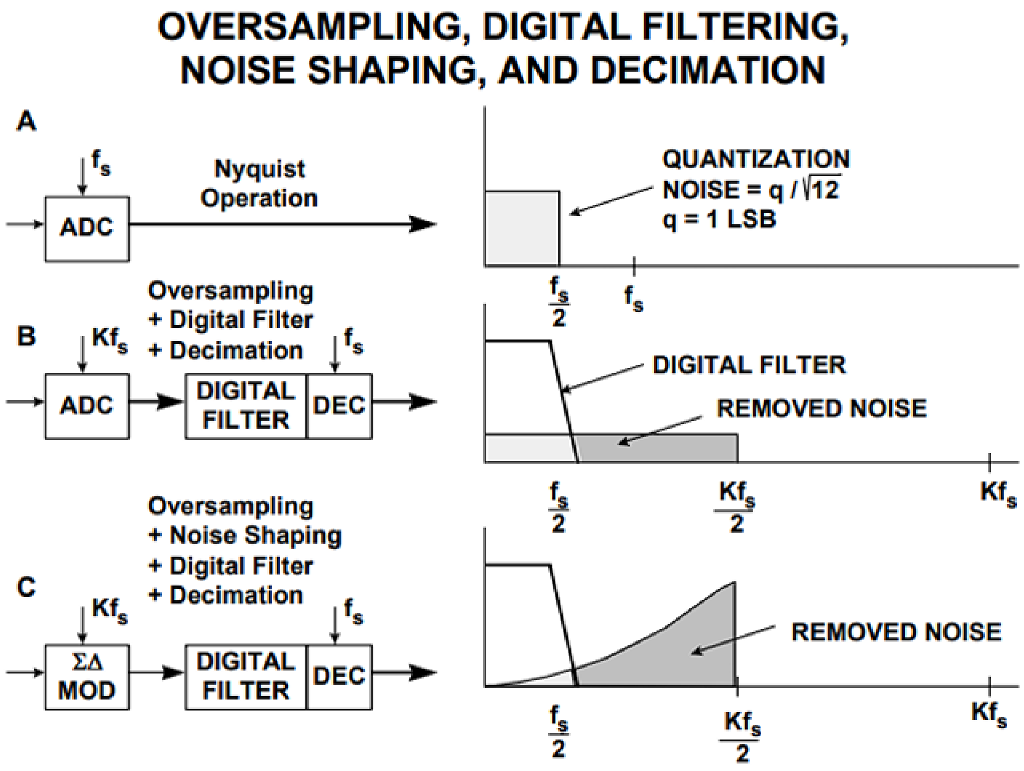


Figure 3.12.: ΣΔ ADC: Oversampling, Filtering, Decimation and Noise Shaping [10]

Data Processing and Analysis

Data Transformation

To get more insights into the signal they are often transformed into the frequency domain. Most used techniques:

- Fourier transform FT
- Short-time Fourier transform STFT
- Wavelet transform WT

Fourier transform

Is used to convert signals form the time into the frequency domain. It is best used for periodic or quasi-periodic signals to identify harmonics which indicate patterns.

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} \, dt$$

Applications:

- Vibration analysis: for eg to identify natural frequencies
- Power spectrum analysis: provides power distribution across the frequencies

If a small window (small part of the signal) is used the frequency resolution is also small.

It should be noted that all the time information is lost using the FT.

Short time fourier transform STFT

The STFT also preserves time information and therefore is suitable for analyzing non-stationary signals. It can show how a signal evolves over time.

Time-Frequency resolution:

- Small window provides good time but poor frequency resolution
- Wide window-> poor time but good frequency resolution

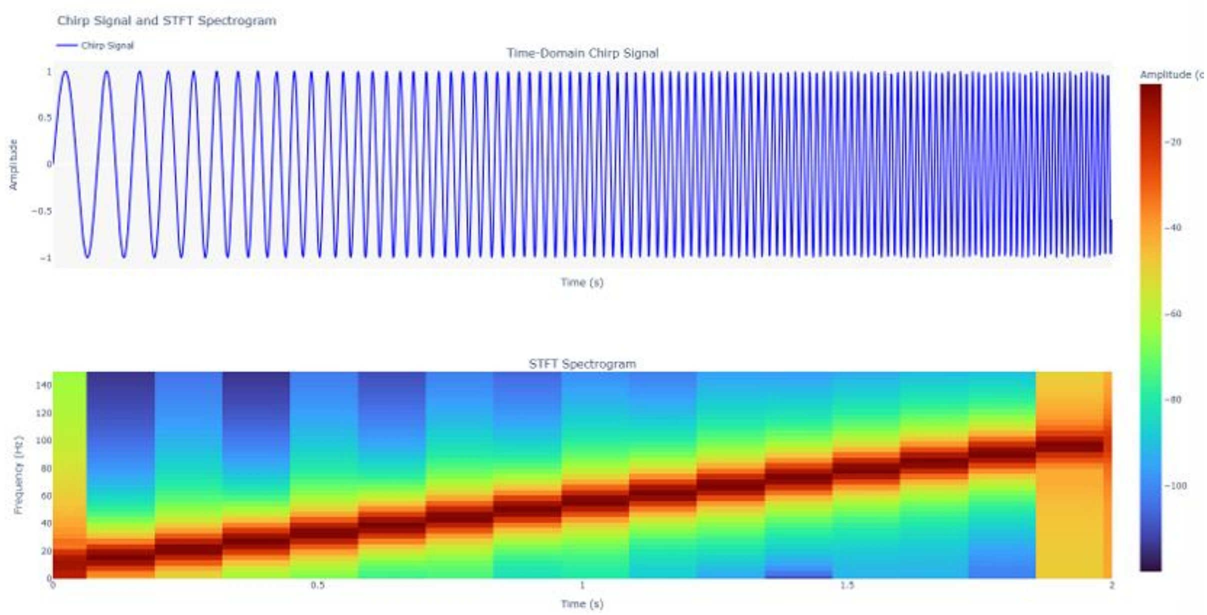


Figure 4.1.: STFT of chirp signal

For the visualization a heat map is used.

Application of the STFT

- Vibration analysis: analyzing transient vibrations
- Biomedical signal processing: ECG, EEG
- Audio Signal processing: detecting beats and identifying instruments

Wavelet transformation WT

Unlike the STFT the WT does not use windows or fixed windows for the transformation but wavelets.

A WT can by imagined with a wavelet that has a given frequency. This wavelet is shifted along the time axis. Then the Areas under the wavelet and the signal are compared to determine how good the wavelet fits the signal (convelution). Then the wavelet is modified for the next frequency and the process is repeated. This gives a result that shows how much energy a certain frequency is contributing to the overall energy of a signal on a given point.

[Wavelets: a mathematical microscope]

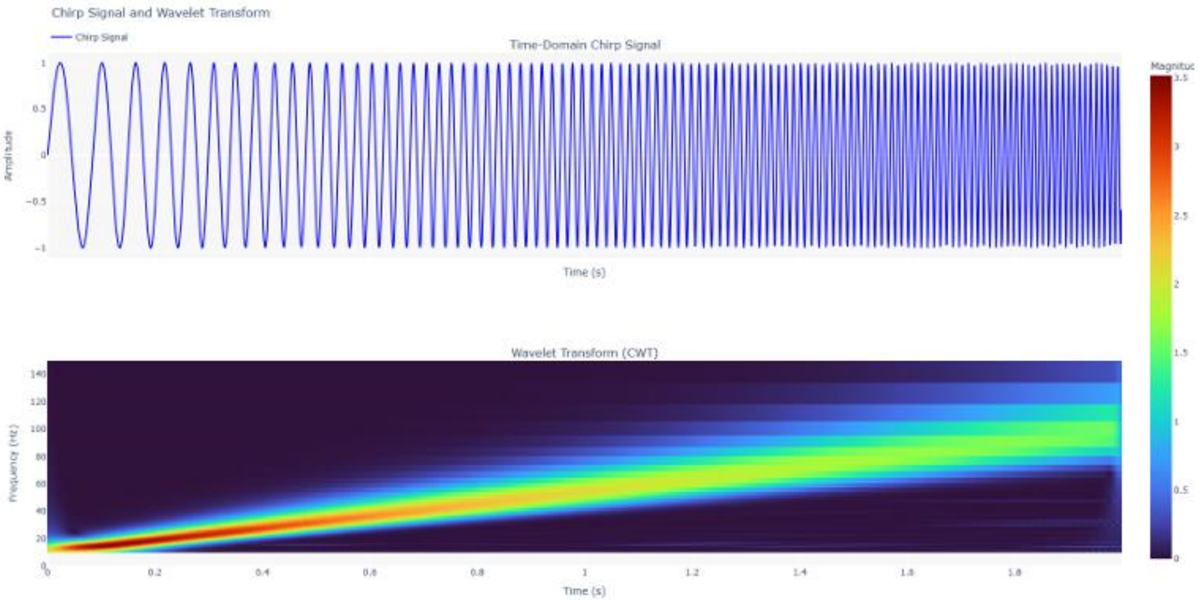


Figure 4.2.: WT of chirp signal

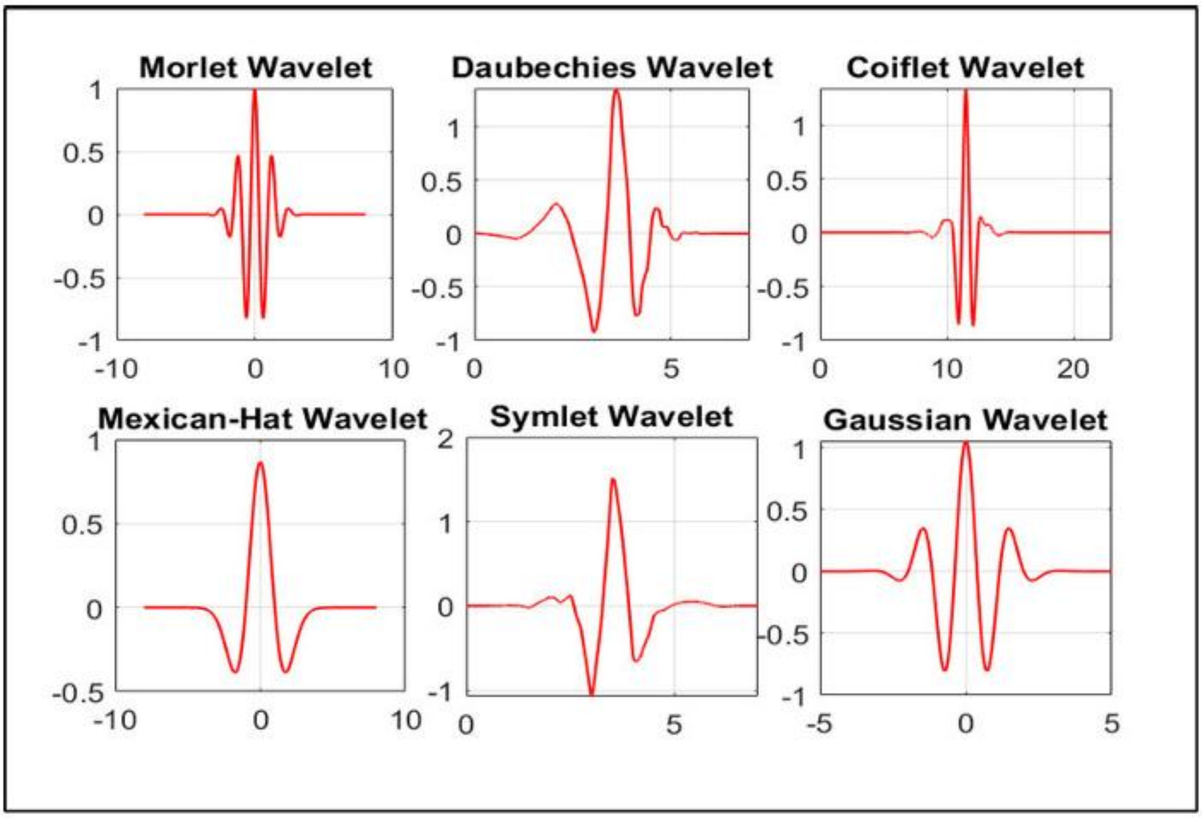


Figure 4.3.: Collection of commonly used Wavelets

The wavelet fullfill:

- Zero mean
- Admissible in the frequency domain
- Should be well localized in time and frequency domain

Heisenberg Boxes:

The purpose of the Heisenberg boxes is to illustrate the uncertainty of the WT. Different wavelets cause different uncertainties in the time and frequency domain. Also they are not equal for every frequency and time point. In general for low frequencies a small uncertainty is wanted in the frequency domain and for larger ones a small uncertainty in the time domain is wanted.

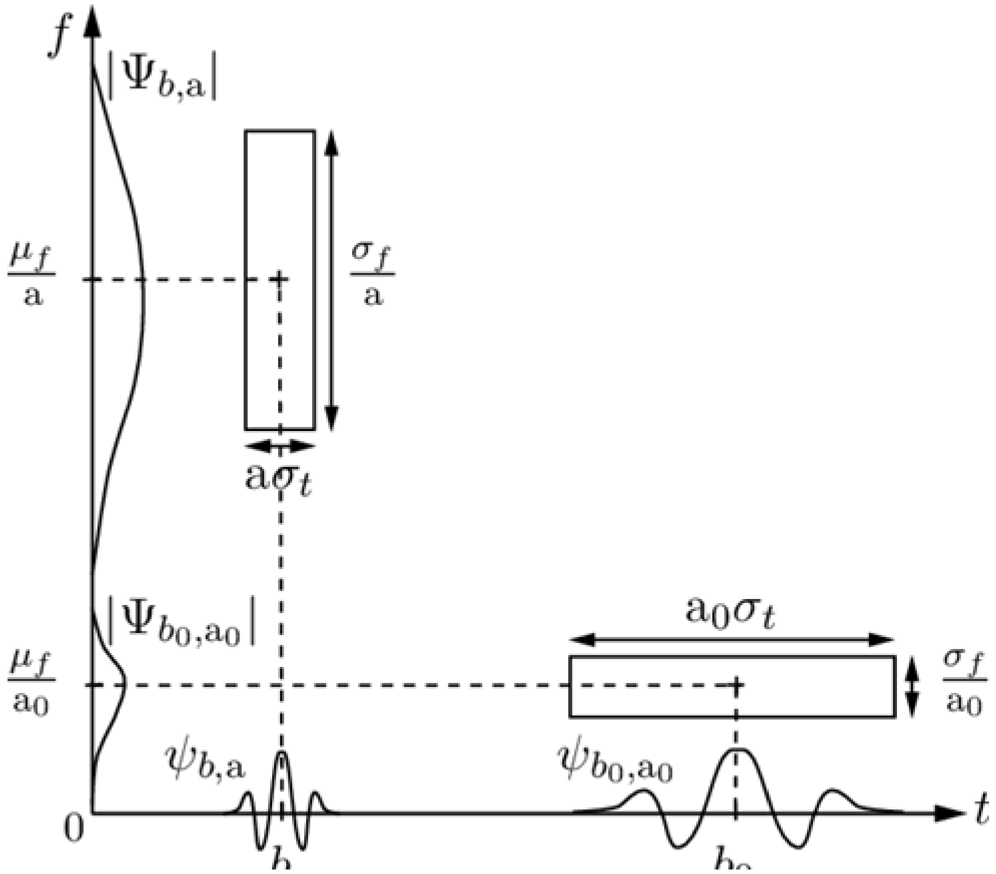


Figure 4.4.: Heisenberg Boxes [3]

Application of WT:

- Denoising signals
- Fault detection in Machinery
- Image processing and compression

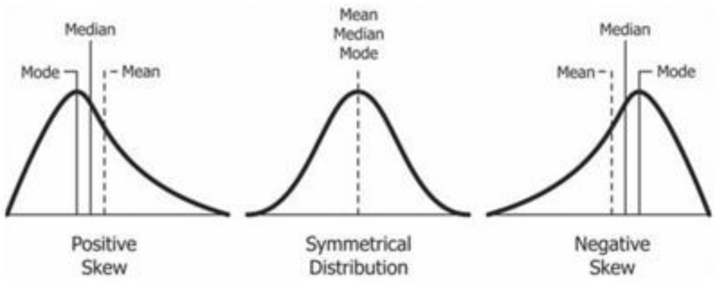
Table 4.1.: Comparison of STFT and Wavelet Transform (WT)

Feature	**STFT**	**Wavelet Transform (WT)**
Basis Function	Sinusoidal (Fourier Transform)	Wavelets (Localized and Scalable)
Time-Frequency Trade-off	Fixed, based on window size	Dynamic, varies across frequency range
Time Resolution	Constant (determined by window size)	High for high frequencies, low for low frequencies
Frequency Resolution	Constant (determined by window size)	High for low frequencies, low for high frequencies
Computational Complexity	Lower (especially for discrete transforms)	Higher, particularly for CWT
Output Representation	Spectrogram (time vs frequency)	Scalogram (time vs frequency, multi-resolution)

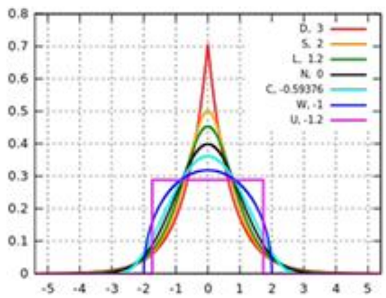
Feature Extraction

Statistical features:

- Mean
- Standard deviation
- Variance
- Mode: indicates most occurring values
- Skewness: quantifies asymmetry of data distribution
- Kurtosis: describes tailendness of distribution



(a) Mean, Median, Mode, and Skewness



(b) Kurtosis

Domain-Specific Features:

- Root mean square: represents energy content in a signal
- Peak amplitude
- Signal envelope

Time domain features:

- Rise time
- Fall time
- Pear duration
- Autocorrelation function: similarity of signal with a time delayed version of itself

Frequency domain features

- Spectral entropy
- Peak frequency
- Bandwidth

Machine Learning ML

ML algorithms are algorithms that don’t have to be specifically programmed to do a task, but rather can be trained, by using appropriate training-data.

Supervised Learning

- Using labeled training data
- Goal is to learn mapping from input to output
- Uses different regression methods:
  - Linear regression
  - Logistic regression (for binary classification tasks)
- Other methods:
  - Naïve bayes
  - Decision trees
  - Support Vector Machines SVM

Unsupervised Learning

- Training data without labels
- Used to find hidden patterns
- Output is unknow before training
- Algorithms:
  - K-Means Clustering
  - DBSCAN Algorithm
  - Principal Component Analysis

Neural Networks

They are a class of supervised learning models. They don't work like normal algorithms, but work in a way inspired by the human brain (hence the name).

They are particularly useful for unstructured data like audio, text and images.

Feedforward Neural Networks FNN

- Are the most basic neural networks
- No cycle or feedback loops
- Architectur:
  - Input layer
  - Hidden layer
  - Output layer

Convolutional Neural Networks CNNs

- Use convolutional layer

- Most often used for images
- Achitecture:
  - Convolutional layer
  - Pooling layer
  - Fully connected layer

Recurrent Neural Networks RNNs

- Designed for sequential data
- Have loops in their structure
  - Maintain information across time steps
- Used for forecasting and natural language processing, text generation

Inertial Measurement Units IMUs

IMUs are very compact and versatile. They often see use in navigation systems and portable electronics.

The consist of several sensors:

- Gyroscopes
- Accelerometers
- Magnetometers

Each of those is integrated to measure across a three-dimensional space.

Microelectromechanical Systems MEMS

MEMS integrate mechanical and electrical components at a microscopic scale on a single chip. They can range in size from micrometers to millimeters.

They are usually manufactured on silicon wafers using photolithography such as devices like CPUs and GPUs.

Components of MEMS:

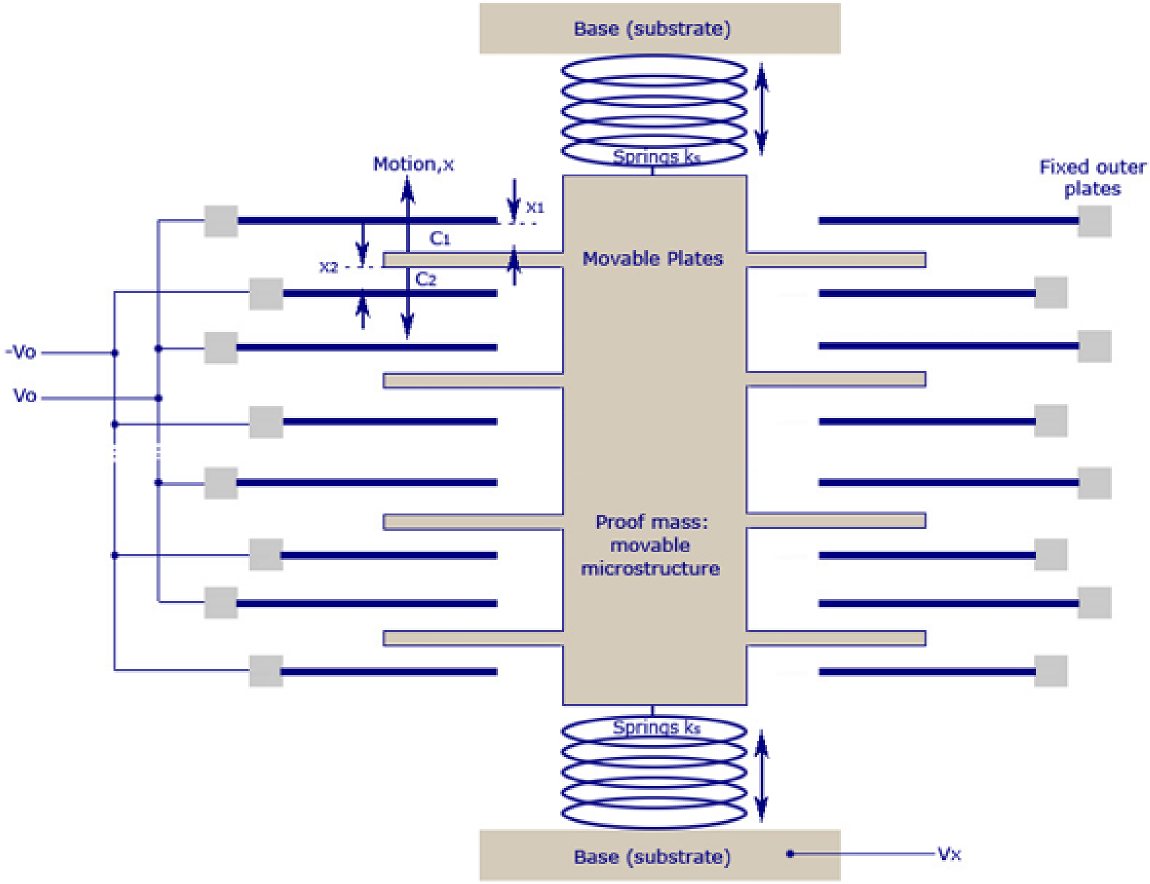
- Masses
- Springs
- Dampers
- Detectors: Capacitors or piezo electric
- Actuators
- Linkages

Advantages of MEMS:

- Small size
- Low cost
- High precision
- Scalability

Accelerometer:

They are based on a spring-damper system. The system responds with displacements to acceleration, which alters the capacitance of the capacitator.



3-Axis Mems

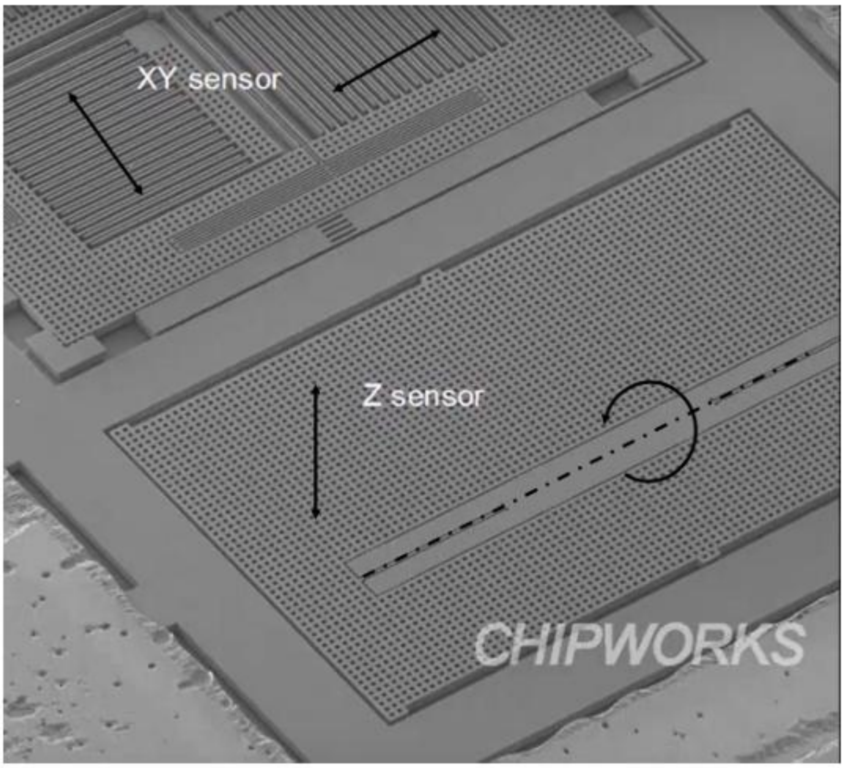


Figure 5.3.: 3-axis MEMS Accelerometer [27]

Gyroscope

A gyroscope measures the angular velocity around the three rotation axis.

Three different technologies are used for that: mechanical, optical, ring laser and MEMS.

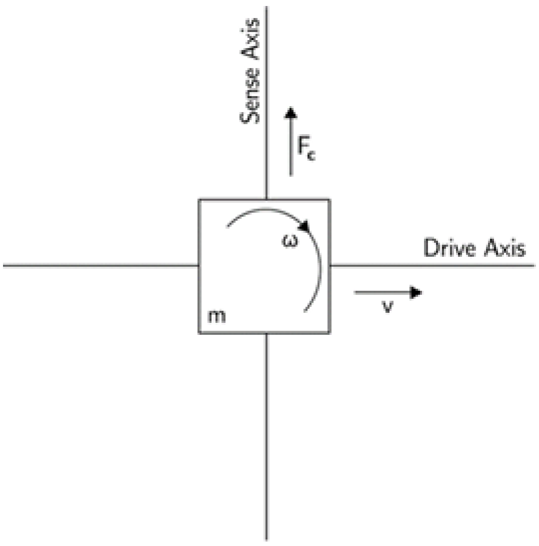


Figure 5.4.: Principle of gyroscope [28]

The gyroscope experiences a time-varying bias, which means the measurement drifts over time.

The gyroscope is also effected by white noise, which is random noise. The resulting error gets progressively bigger with time. This means that the uncertainty gets bigger over time.

Magnetometer

A magnetometer consists of three Hall-effect sensors. These sensors are used to measure the magnetic field of the earth. It provides data regarding the attitude (Haltung/Orientierung) and can be used to correct the time dependent drift of the gyroscope.

Types of systematic errors in IMUS:

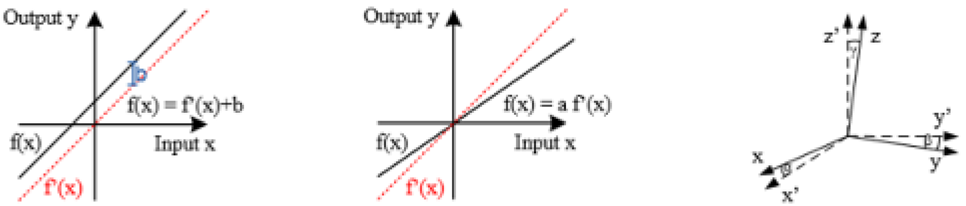
- Constant offset
- Moving bias
- Measurement noise
- Random walk
- Scale factor (gain) error
- Misalignment of the axes
- Non-orthogonality of axis
- Temperature drift

Correction:

- Sensor calibration
- Temperature compensation
- Dynamic calibration

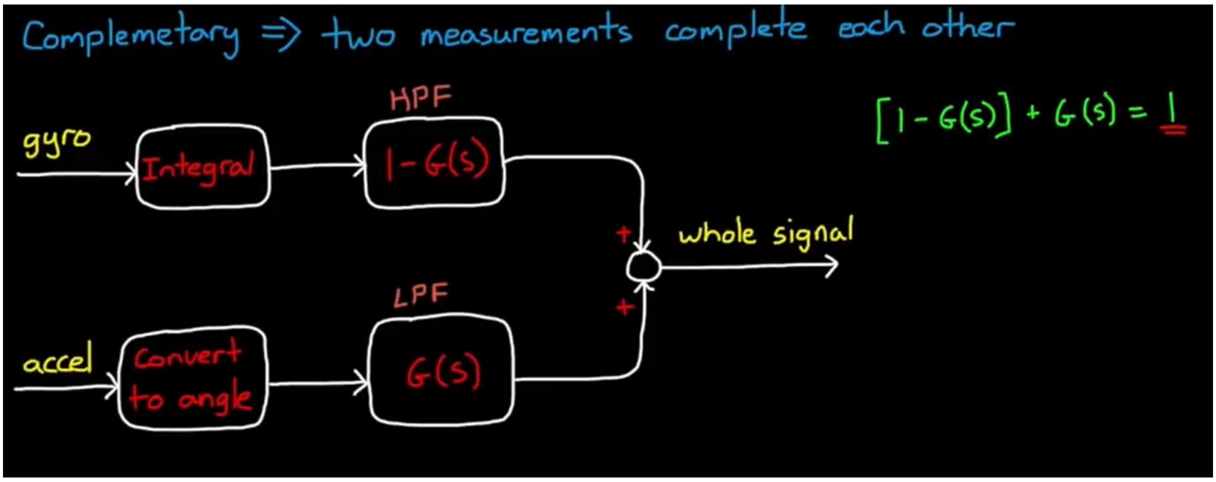
Systematic Errors in IMU data:

- Offset error (a)
- Scale factor error (b)
- Angle misalignment ©



(a) (b) (c)

Complementary Filter



Complementary Filters are used, if one measurement signal is used to correct another one. Like in the Image above the data of the accelerometer is used to correct the drift of the gyroscope. Here for the acceleration a low pass filter (Gs) is used and its complimentary part is used for the gyro (1-Gs), which happens to be an high pass filter. This can also be done with only gains for example. But watch the fucking video for a better explanation.

[Drone Control and the Complementary Filter]