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College of Engineering and Petroleum

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ME319 MECHATRONICS

Part III: The Senses – Sensors and Signals

Lecture 2: Sensor Characteristics

Spring 2021

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Lesson Objectives

- Review common characteristics of sensors
- Discuss the characteristics of sensors in the context of a real sensor example

What is a sensor

- A device that measures a physical variable to a measurable electrical signal
  - *Physical Variable: Pressure, Temperature, Force, etc.*
    - *Referred to as the **measurand***
  - *Output can be analog or digital*
  - *Analog: Current or Voltage*
- Sensors are a subset of transducers
  - **Transducers**: devices that convert to and from physical variables and electric signals, including **actuators**.

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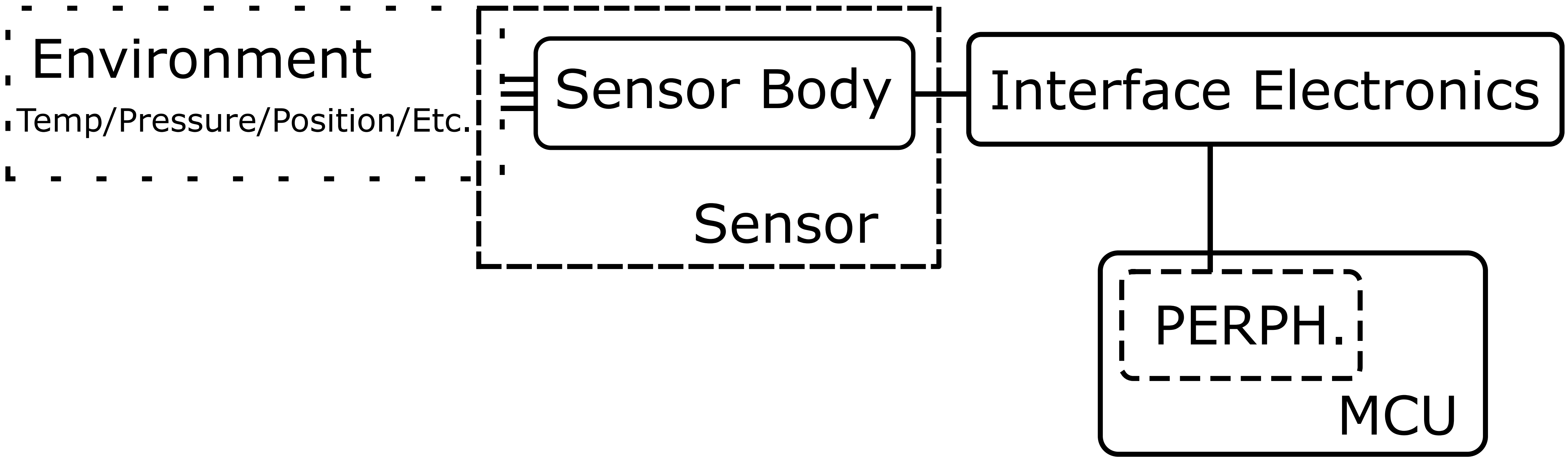
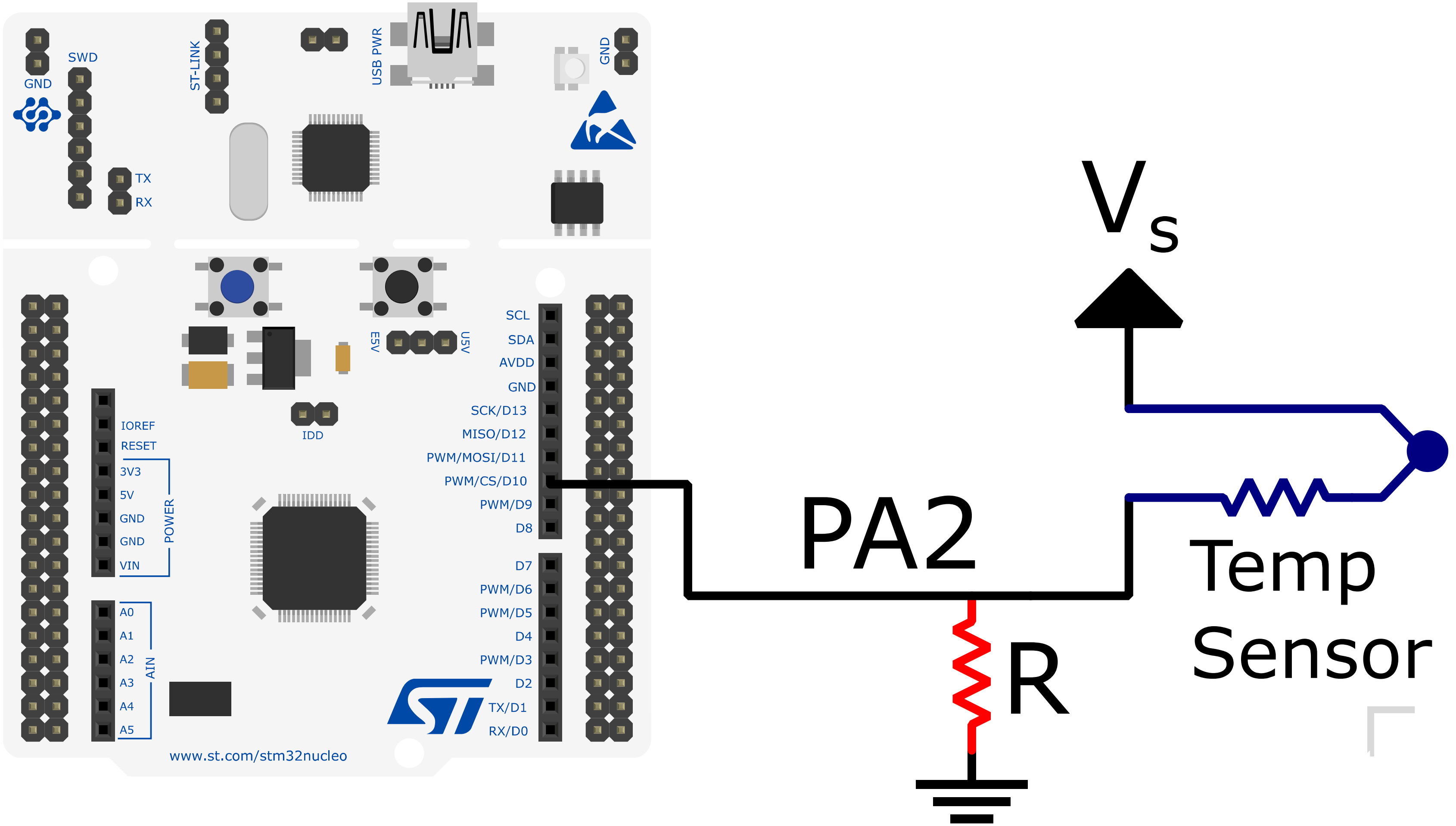
- The physical measure is the **measurand**

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GND
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MISO/D12
PWM/MOSI/D11
PWM/CS/D10
PWM/D9
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PWM/D6
PWM/D5
D4
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V_s
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Sensor

Sensor Performance Characteristics

- Sensors are not magical perfect devices
- They vary, they have limitations
- Sensor performance characterized through:
  - *Transfer Function*
  - *Sensitivity*
  - *Span / Dynamic Range*
  - *Accuracy*
  - *Precision / Repeatability*
  - *Nonlinearity*
  - *Stability*
  - *Hysteresis*
  - *Noise*
  - *Resolution*
  - *Bandwidth*

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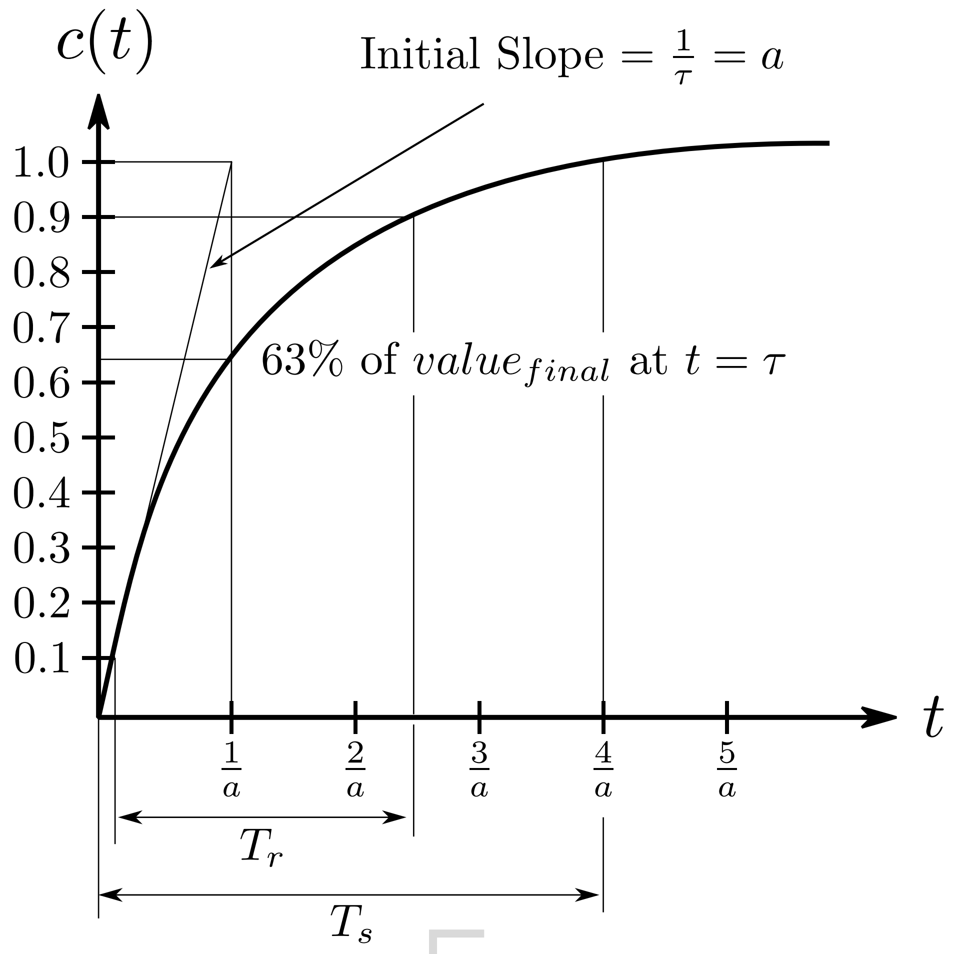
- A sensor is a dynamic system
- Understanding dynamic behavior is important
  - *Especially in feedback control applications.*
- It has transient and steady-state response characteristics
- Many sensors behave as first-order systems, some are higher order.



- **Rise Time T_r**: Time it takes to go from 10 to 90% of F.V.
- **Time Constant τ**: Time it takes to reach 63% of F.V.
- **Settling Time T_s**: Time to reach 2% within F.V.

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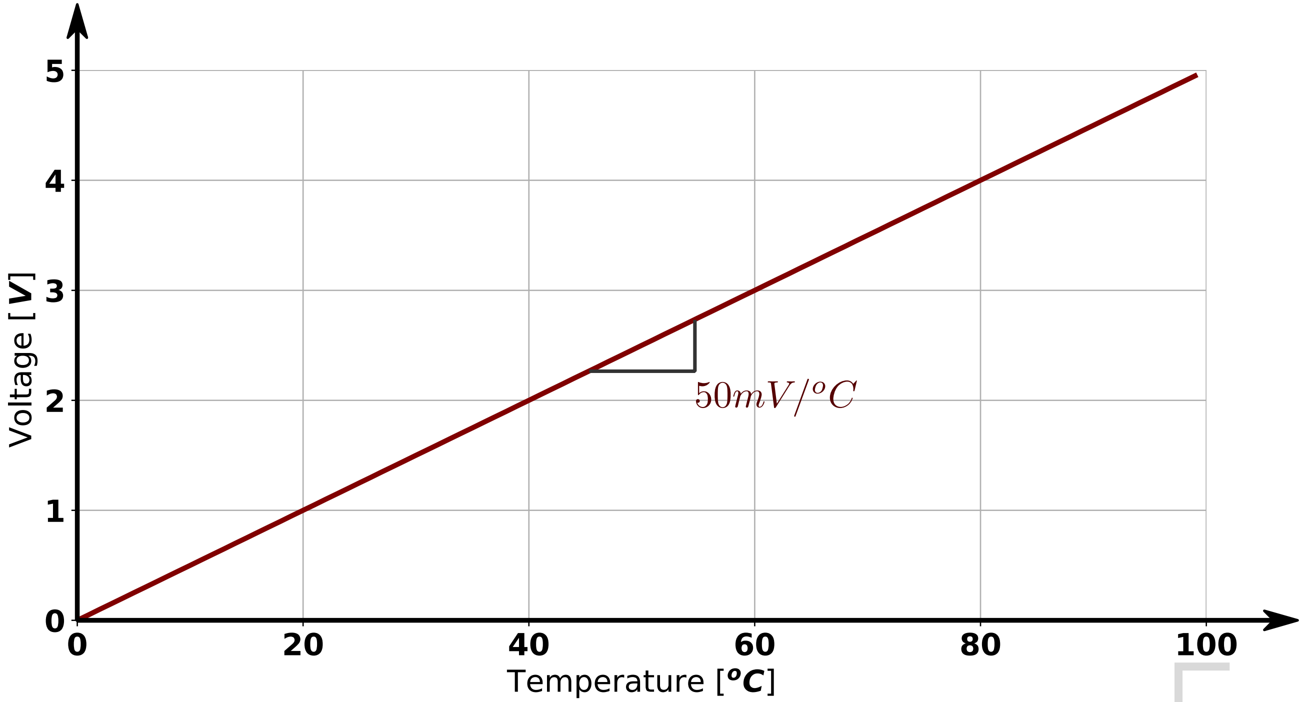
- Relationship between **measurand** and sensor output
  - If the relationship is linear. The sensitivity is the **slope**.
  - Also called: **Sensor Gain**, or Scale Factor

$$Output = Gain \times Sensitivity + Bias$$

$$V[V] = \frac{50}{1000} T[^0C]$$



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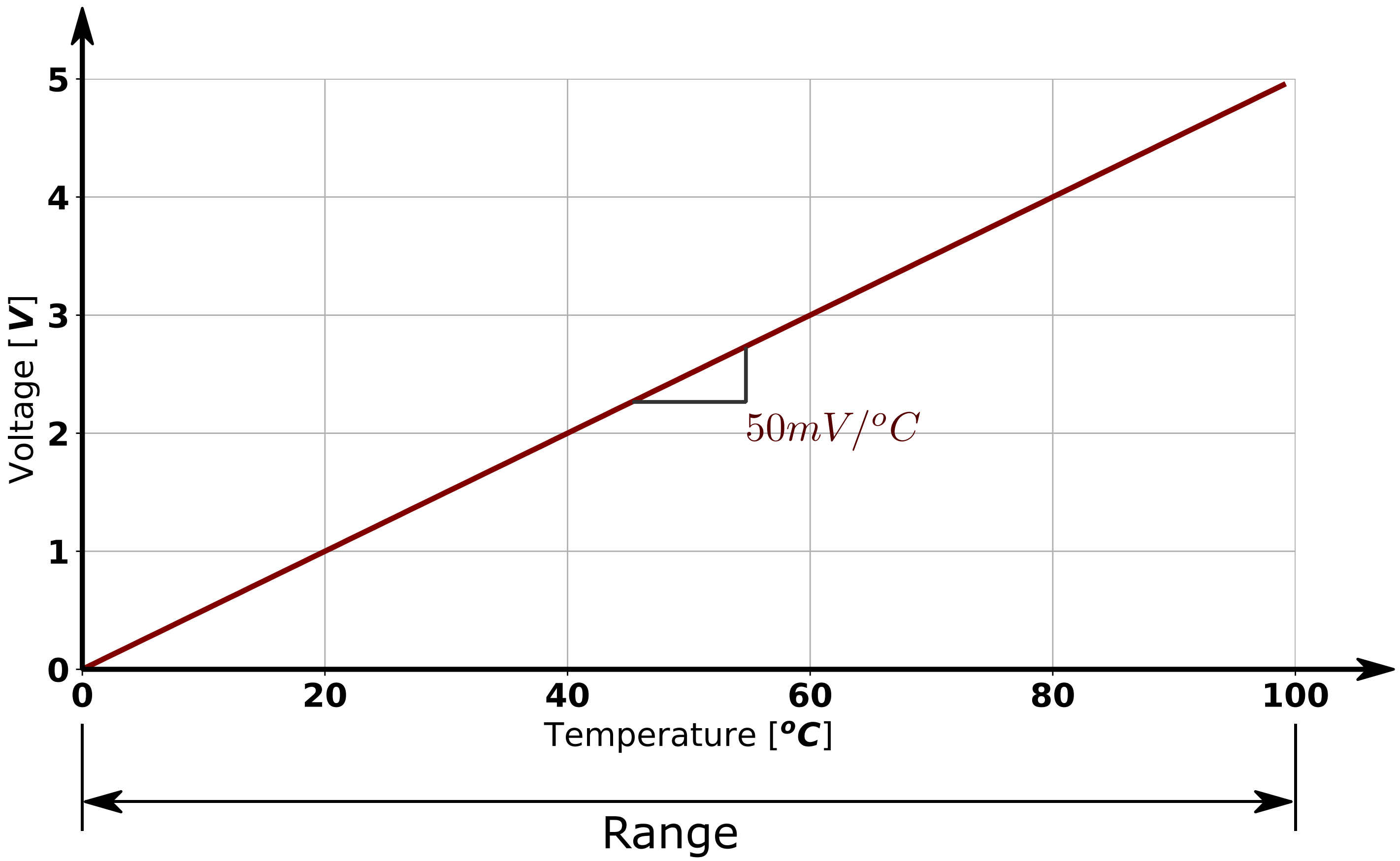
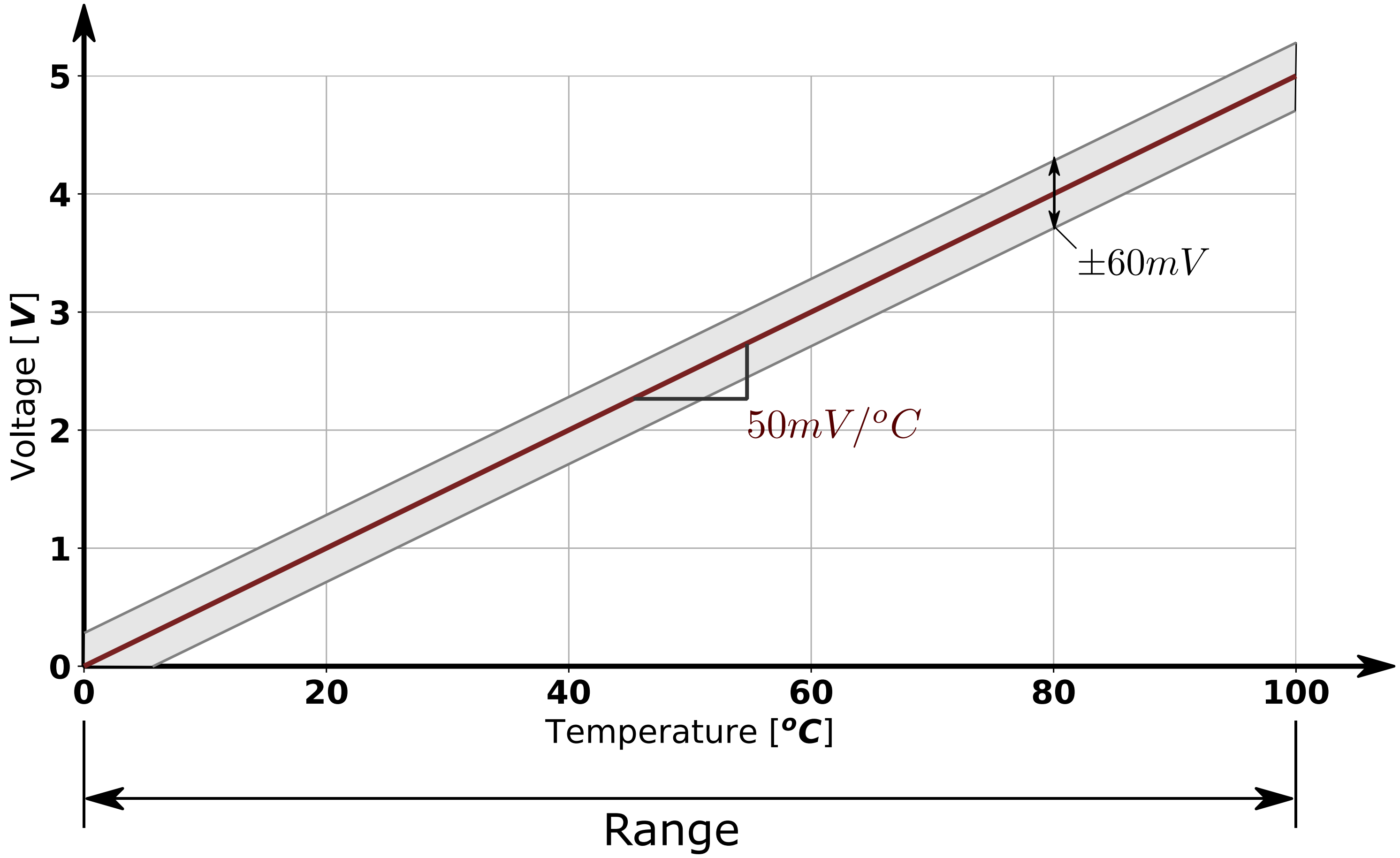
- Range of physical quantity that can be detected by the sensor
  - If sensor can output $0 - 5V$, with Sensitivity $50mV/^oC$:
    - **Range**: $0 - 100^oC$

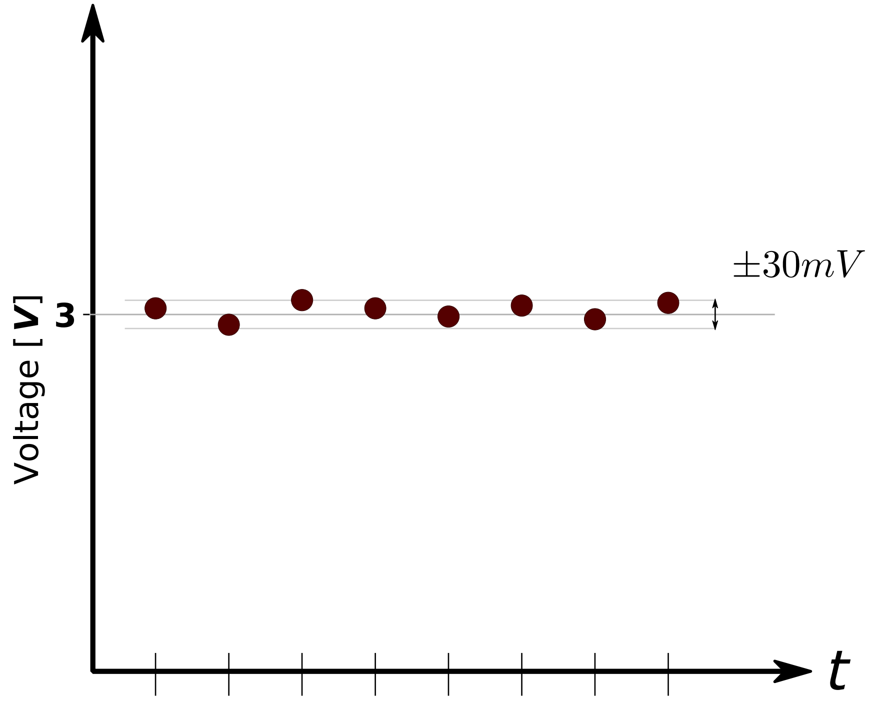


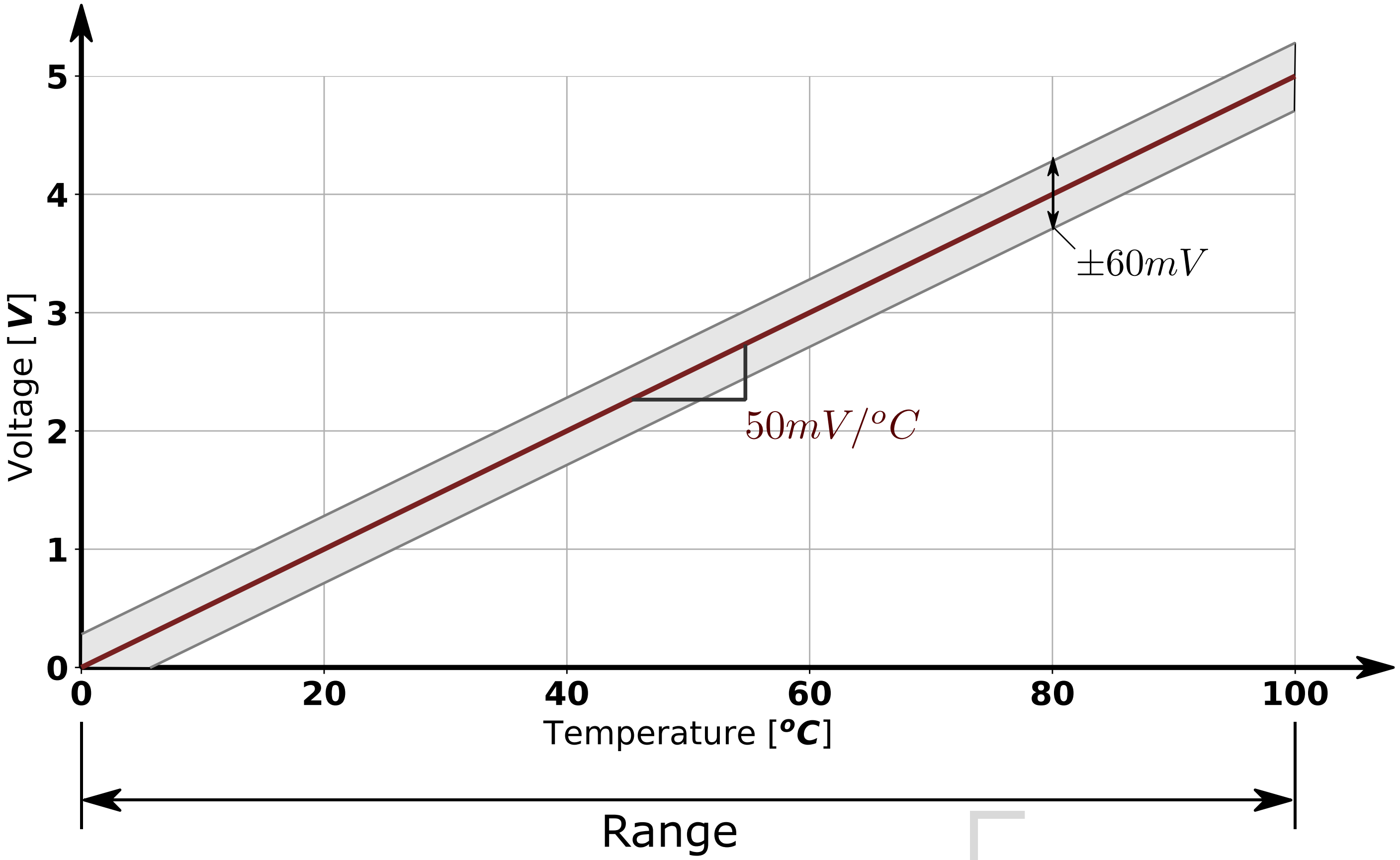
Accuracy

- Deviation between true and measured value
  - Usually expressed as a percentage of Full-Scale Value (F.S.V)
- Expressed as an error bound. E.g: $\pm 2 units$

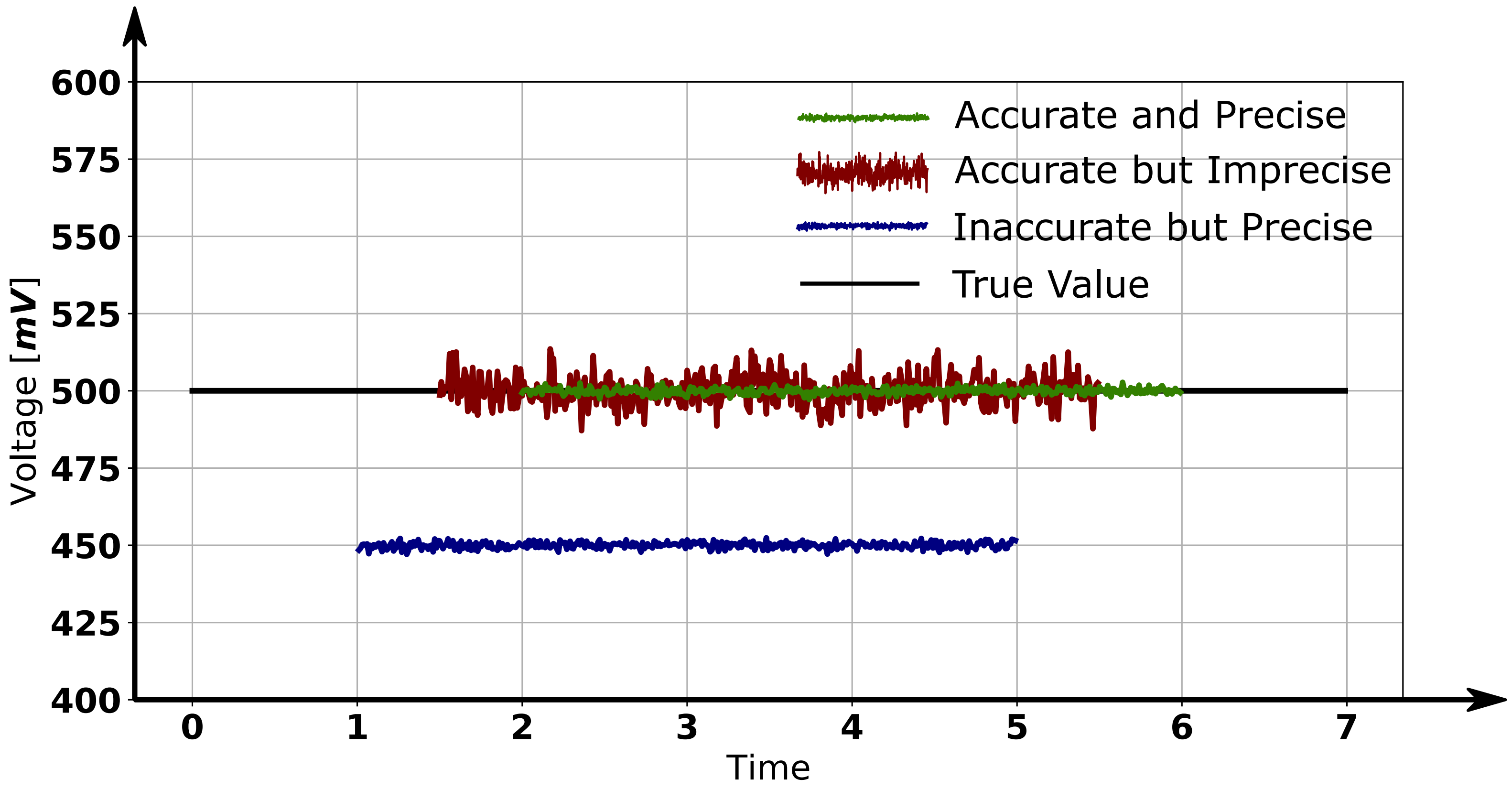


- Error in output for repeated measurement of same physical quantity

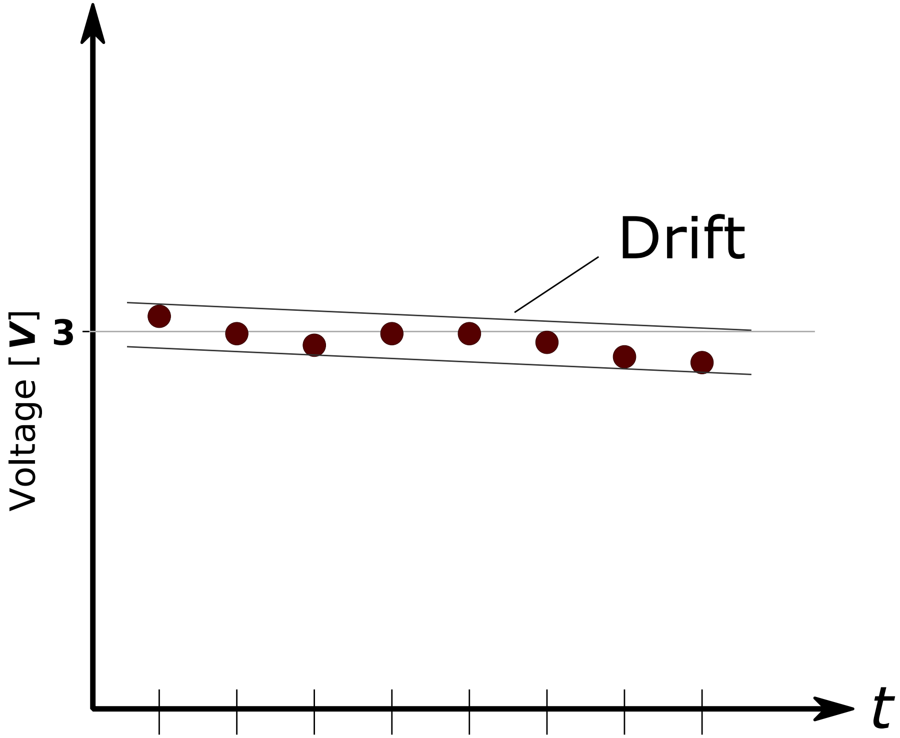


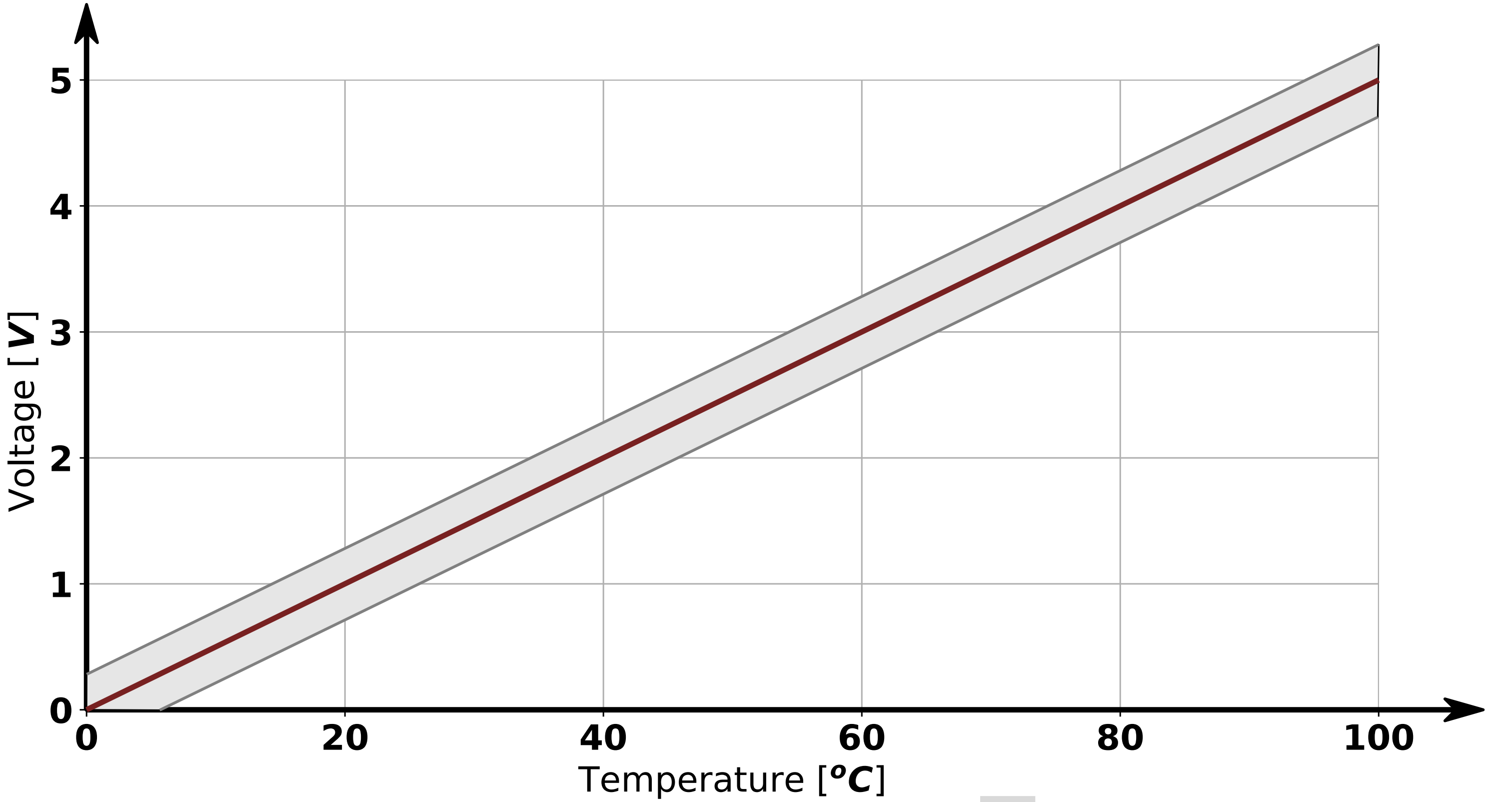


- Accuracy: Output is near measurand
- Precision: Output is consistent

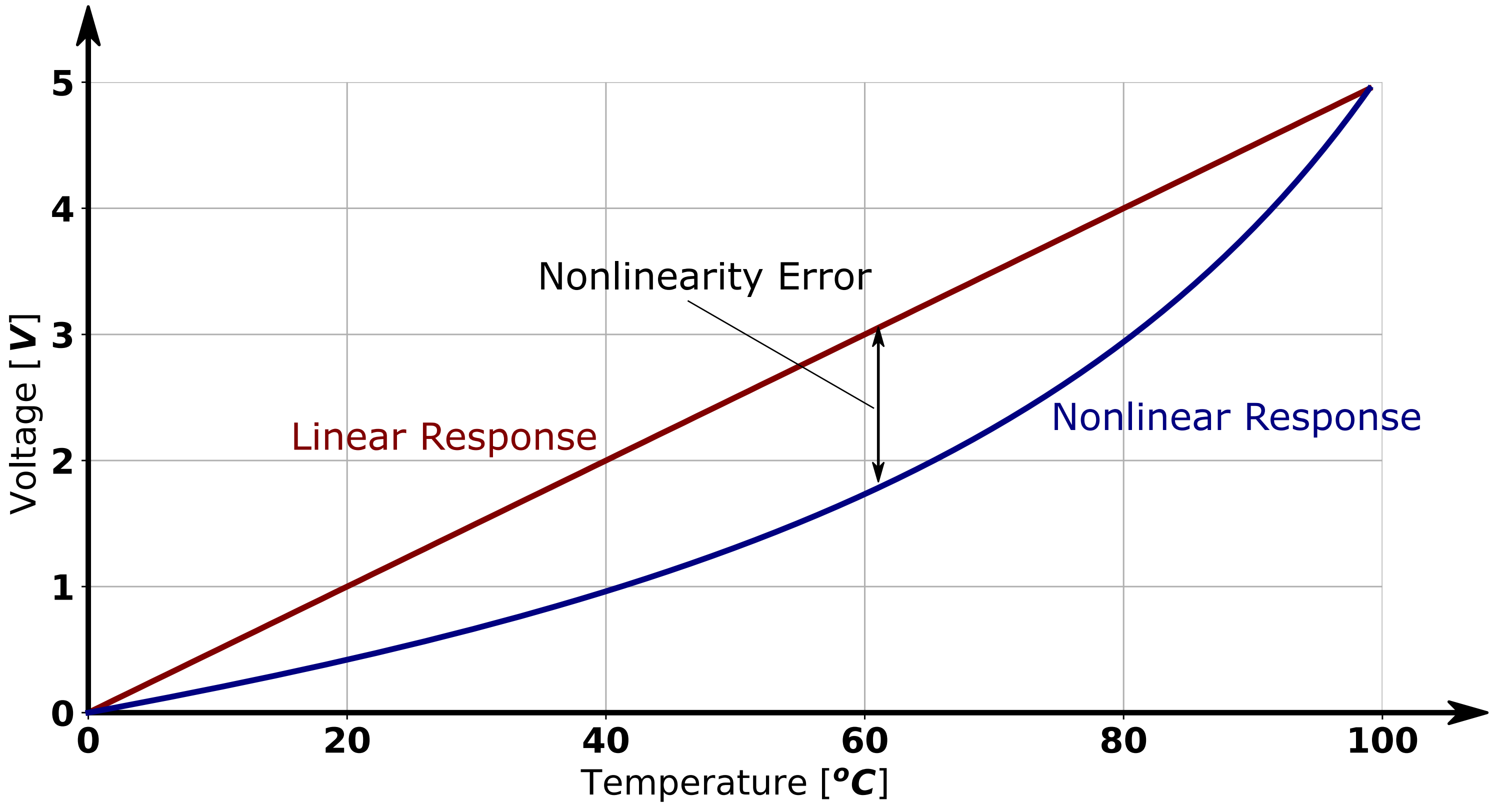


- Variation in sensor **output** with **time** while the measurand is not changing.

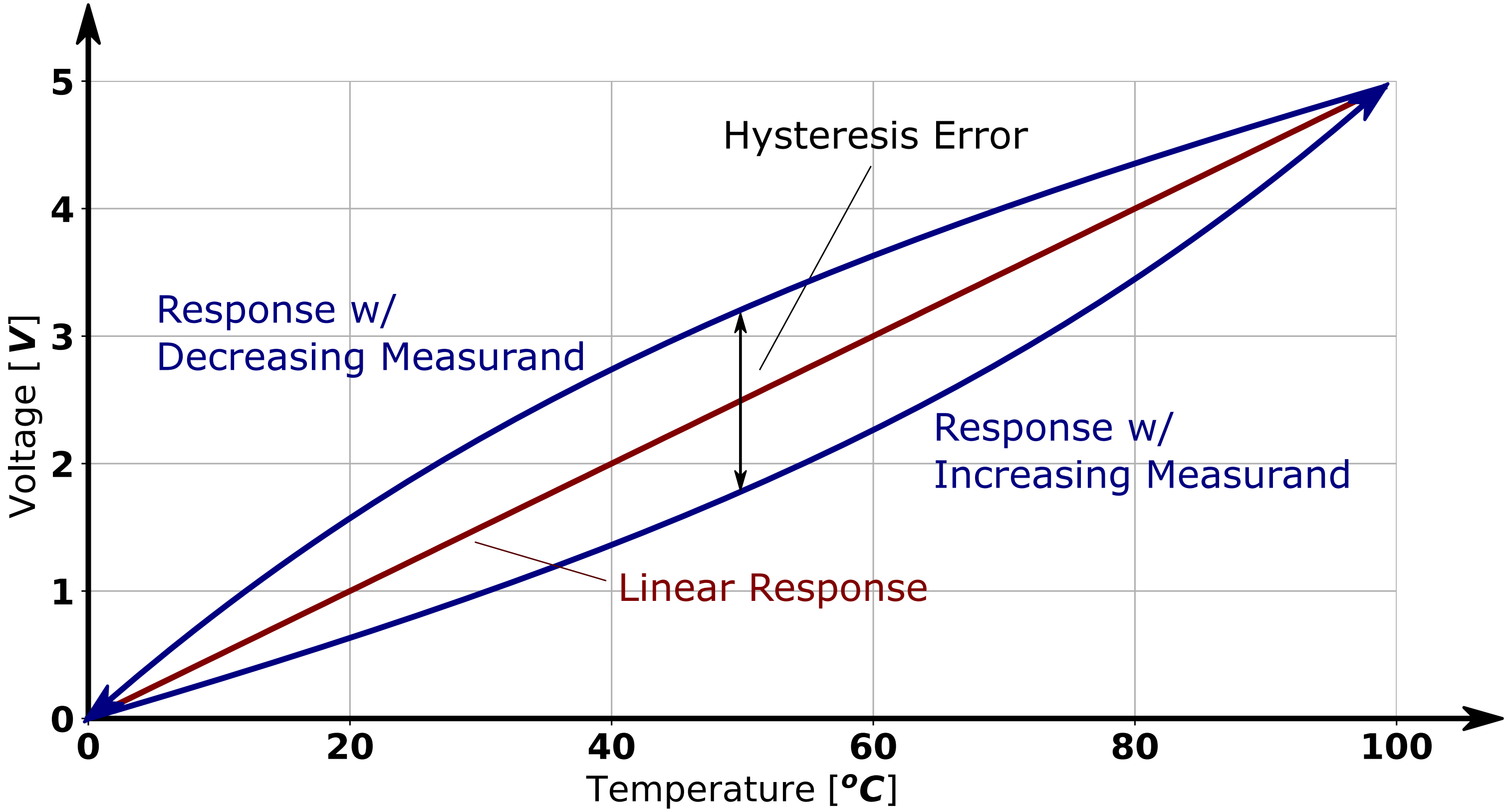




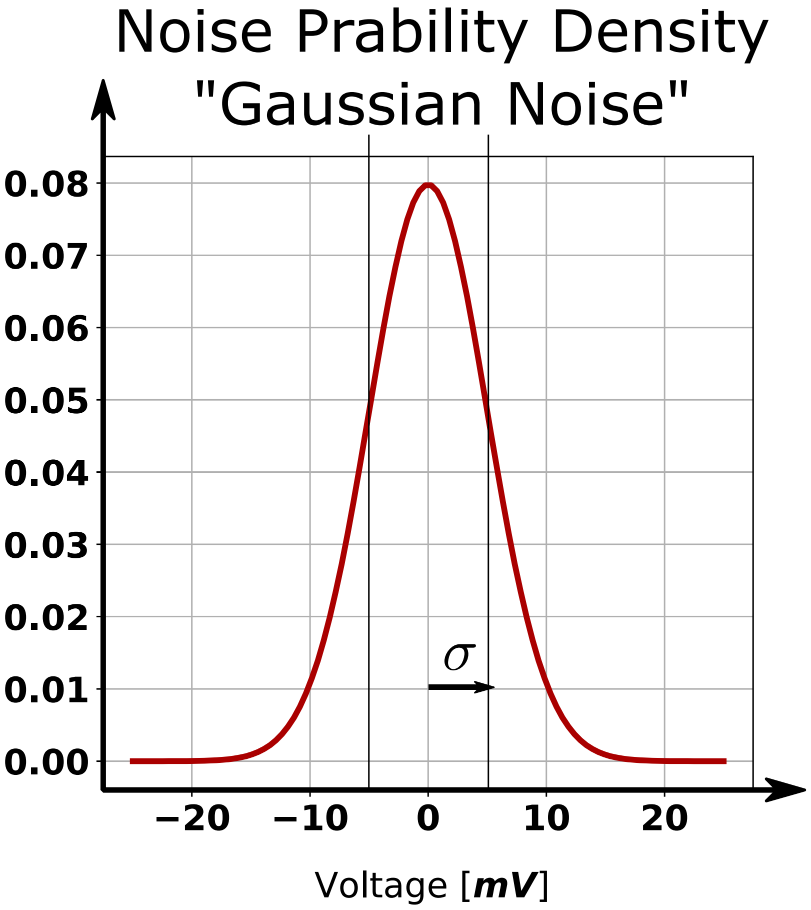
- **Nonlinearity**:
- *If the relationship between measurand and output is not a **straight line**.*
- **Nonlinearity Error**:
- *Maximum difference between sensor **output** and a straight line fit.*

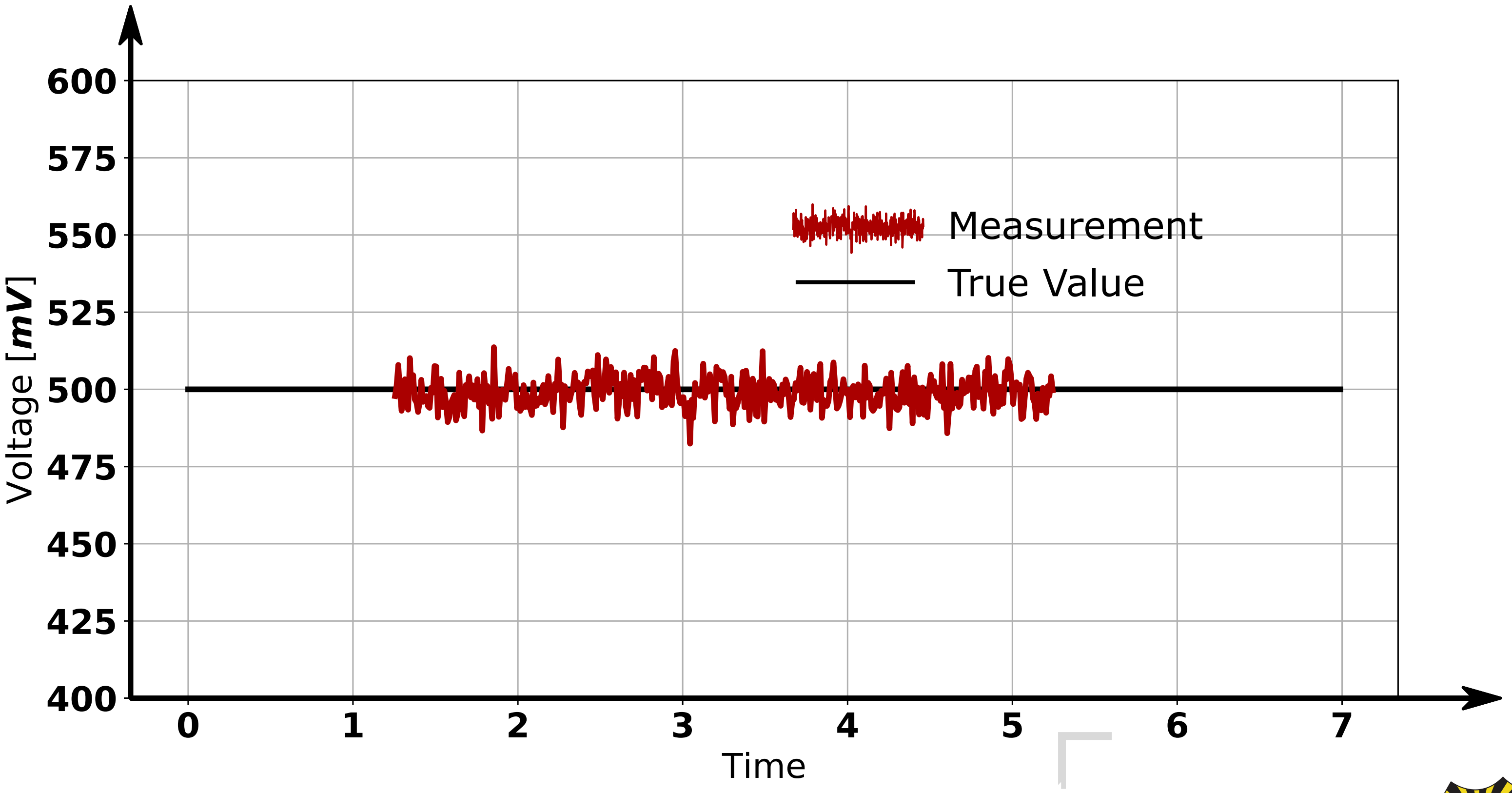


- Output values when measurand is increasing, are different than when measurand is decreasing
- Hysteresis Error: Maximum difference in sensor output between measuring increasing input and measuring decreasing input.



$$Output = True\,Value + v, \quad v \sim N(0, \sigma)$$





Noise

- Added values in the sensor output that don't represent the measurand
- Caused by disturbances in the measurand environment or electronics
- Usually higher frequency than measurand's
- Noise can be characterized as Gaussian
  - ***Zero-mean (average noise = 0), with a specific standard deviation σ***
- Noise can be characterized as White-Noise
  - ***Spectral Noise Density is the same for all frequencies.***

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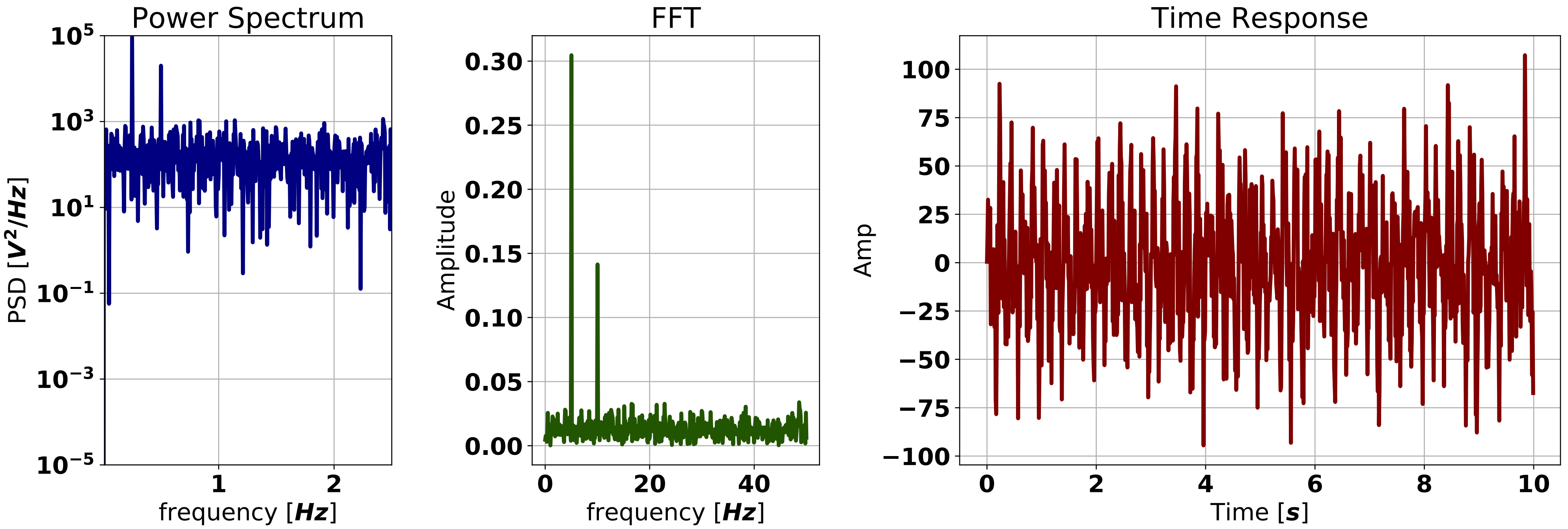
- Noise can be decomposed by frequency using a **spectral density function** $S(f)$
  - Or decomposed using a **Fast Fourier Transform** (FFT)
- Spectral density defines how variance of data is distributed over frequency domain

$$x(t) = 20\sqrt{2}sin(2\pi 5t) + 10\sqrt{2}sin(2\pi 10t) + w(t), w \backsim N(0, 500)$$



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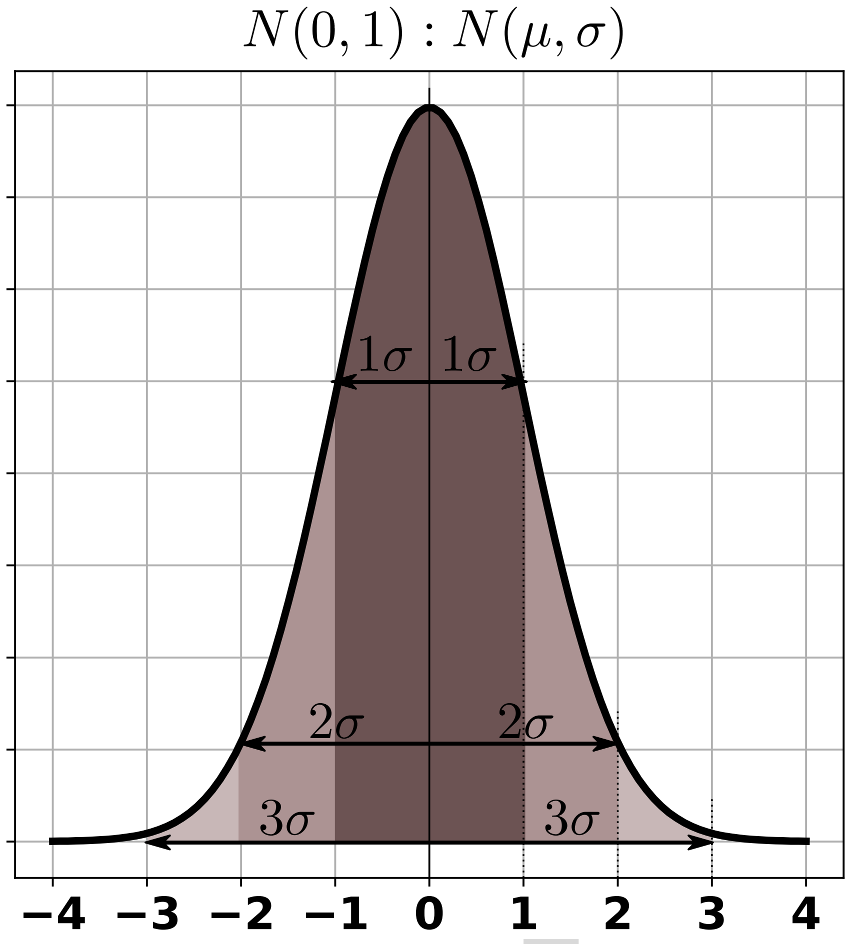
- Noise $w \sim N(0,1)$: $N(\mu, \sigma)$
  - Denotes a normally distributed noise with a standard deviation of 1
  - A random value with an average of 0
  - 68.27% of the values are within

    $[\mu - \sigma, \mu + \sigma] = [-1,1]$



- Noise is often characterized by the Root-Mean-Square
- Where noise, $w(t)$, is a zero-mean normally distributed

$$\underbrace{\bar{w}}_{Noise\ Mean} = \lim_{t\to\infty}\frac{1}{t}\int_{-t/2}^{t/2} w(t)dt = 0,$$

$w \sim N(0, \sigma)$: Normal Distribution, Zero-Mean, Stand. Deviation σ

- The noise mean square is not zero

$$\underbrace{\overline{w^2}}_{Noise\ Mean\ Square} = \lim_{t\to\infty}\frac{1}{t}\int_{-t/2}^{t/2} w^2(t)dt \neq 0$$

- The Root-Mean-Square (RMS) of noise:

$$w_{RMS} = \sqrt{\overline{w^2}}$$

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External Noise

- When designing mechatronic systems, need to be aware of nearby signals that interfere with sensors
- Noise can interfere with electrical signal
  - *Examples: EMI, Inductive Coupling*
- Noise can interfere with measurements
  - Emitted by actuators or surrounding environment
  - *Examples:*
    - *Use of magnetometers near motors*
    - *Use of ultrasonic proximity sensors near motors*
    - *Use of pressure sensors near rotors*

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- Smallest change in measurand value that will produce an observable change in the output value
- Resolution is quoted in the units of the measurand or output
- If the sensor's interface is digital: *resolution is often limited by sensor's ADC*
- If the sensor's interface is analog: *resolution is often limited by MCU's ADC*
- A sensor's resolution may be limited by noise.
  - *In this case, resolution is quoted in* $physical\ signal/\sqrt{Hz}$

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Bandwidth

- The range of frequencies of an input physical signal that a sensor can detect
- Sensors cannot capture signals oscillating at very high frequencies
  - Some sensors cannot detect signals oscillating at low frequencies
- The range of frequency for which the sensor can respond is the **Bandwidth**
  - *Bandwidth is often quoted in **Hertz***
- A sensor is a **dynamic system**, recall the transfer function.
  - It may behave as a low-pass filter, where input with frequencies higher than cut-off frequency get **attenuated**.

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- A sensor can either provide:
- **An analog interface**
  - Usually as a voltage signal, which may need conditioning, then connected to the ADC of Microcontroller.
- **A digital interface**
  - A simple binary state (e.g. switch or optical encoder)
  - Data sent through a communication protocol (e.g. UART, I^2C, SPI)

- Some sensors are available with either interface

Analog Interface

(+) Can provide faster sampling

(+) Conditioning signal under designer control

(-) Complex, Cost

Digital Interface

(+) Can provide cleaner/packaged integration – simple

(+) Onboard processing can allow sensor configuration

(-) Limited by MCU (DAQ) sampling and processing capability

Example - Invensense MPU 6000

- Consider the Invensense MPU 6000 6-axis Inertial Measurement Unit
  - Contains a 3-axis accelerometer,
  - A 3-axis gyroscope,
  - In addition to processing unit onboard.
- Let's review the sensor characteristics of the accelerometer onboard.

5.2 Accelerometer Features

The triple-axis MEMS accelerometer in MPU-60X0 includes a wide range of features:

- Digital-output triple-axis accelerometer with a programmable full scale range of ±2*g*, ±4*g*, ±8*g* and ±16*g*
- Integrated 16-bit ADCs enable simultaneous sampling of accelerometers while requiring no external multiplexer
- Accelerometer normal operating current: 500μA
- Low power accelerometer mode current: 10μA at 1.25Hz, 20μA at 5Hz, 60μA at 20Hz, 110μA at 40Hz

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Example - Invensense MPU 6000 - Accelerometer

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS	NOTES
ACCELEROMETER SENSITIVITY						
Full-Scale Range	AFS_SEL=0		±2		*g*	
	AFS_SEL=1		±4		*g*	
	AFS_SEL=2		±8		*g*	
	AFS_SEL=3		±16		*g*	
ADC Word Length	Output in two's complement format		16		bits	
Sensitivity Scale Factor	AFS_SEL=0		16,384		LSB/*g*	
	AFS_SEL=1		8,192		LSB/*g*	
	AFS_SEL=2		4,096		LSB/*g*	
	AFS_SEL=3		2,048		LSB/*g*	
Initial Calibration Tolerance			±3		%	
Sensitivity Change vs. Temperature	AFS_SEL=0, -40°C to +85°C		±0.02		%/°C	
Nonlinearity	Best Fit Straight Line		0.5		%	
Cross-Axis Sensitivity			±2		%	

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Example - Invensense MPU 6000 - Accelerometer

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS	NOTES
ZERO-G OUTPUT						
Initial Calibration Tolerance	X and Y axes		±50		m*g*	1
	Z axis		±80		m*g*	
Zero-G Level Change vs. Temperature	X and Y axes, 0°C to +70°C		±35			
	Z axis, 0°C to +70°C		±60		m*g*	
SELF TEST RESPONSE						
Relative	Change from factory trim	-14		14	%	2
NOISE PERFORMANCE						
Power Spectral Density	@10Hz, AFS_SEL=0 & ODR=1kHz		400		μ*g*/ √Hz	
LOW PASS FILTER RESPONSE						
	Programmable Range	5		260	Hz	
OUTPUT DATA RATE						
	Programmable Range	4		1,000	Hz	
INTELLIGENCE FUNCTION INCREMENT			32		m*g*/LSB	

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An FFT plot for a gyroscope data collected onboard a drone is shown. The gyroscope data is unfiltered.

The data was collected while the drone was undergoing cyclic and sinusoidal rotation

What filter would you choose and what is the cut-frequency