Automotive Sensors

Wheel Speed Sensor and Inertial Measurement Unit (IMU)

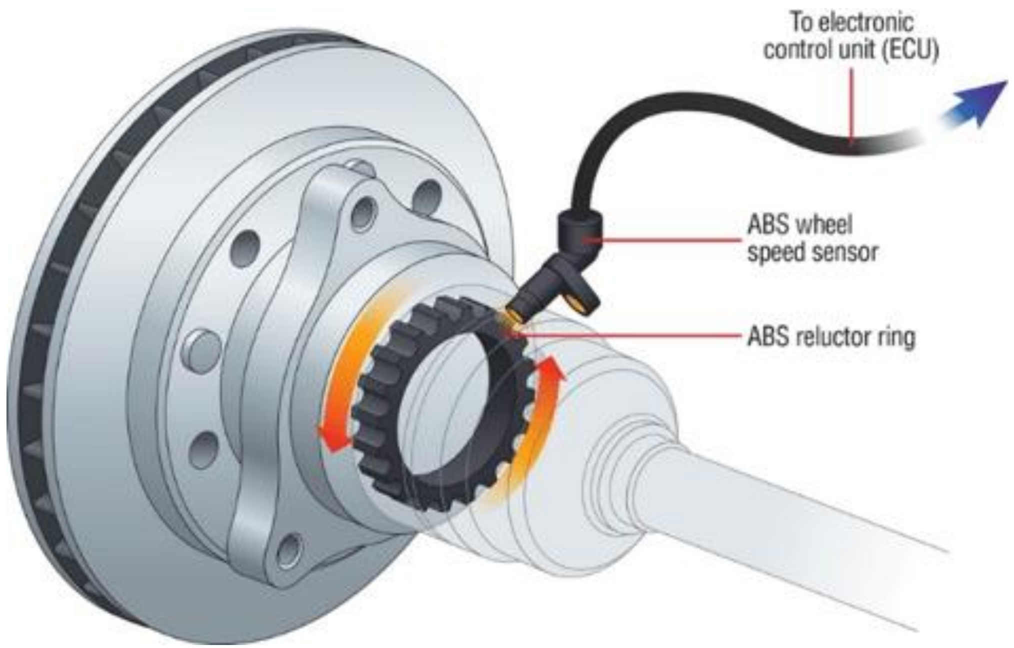
Automotive Intelligence Lab.

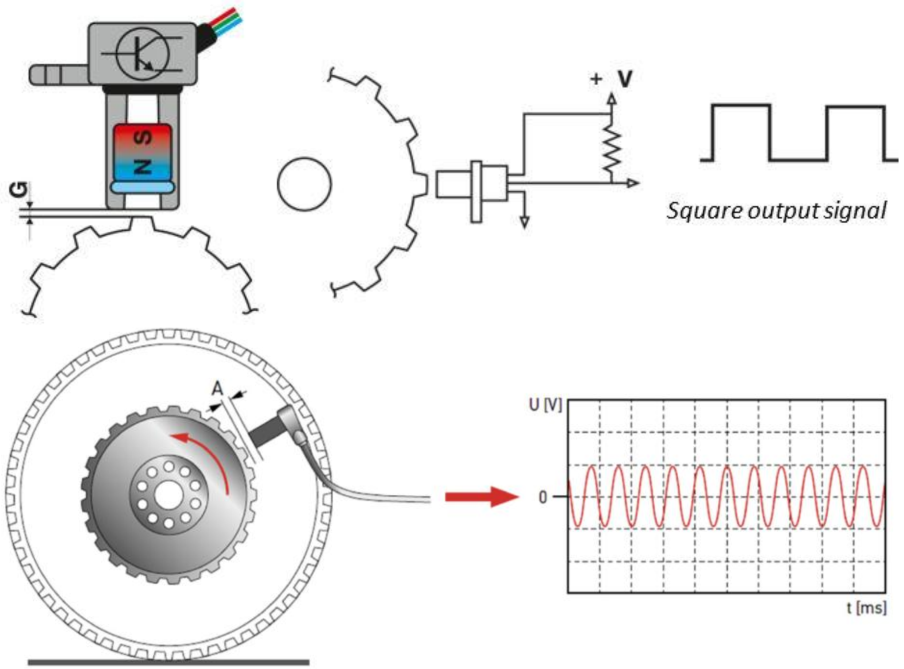
Contents

Wheel Speed Sensor

Wheel Speed Sensor

- Wheel speed sensor is used to count the number of times the motor has rotated.
- Wheel speed sensor can be used to calculate the distance that the robot has driven or turned.
- Signals and measurements
  - Signals: pulses generated during rotational motion.
  - Measurements: amount of rotation, wheel speed, angle, or other relevant parameters.





Process of Wheel Speed Sensor

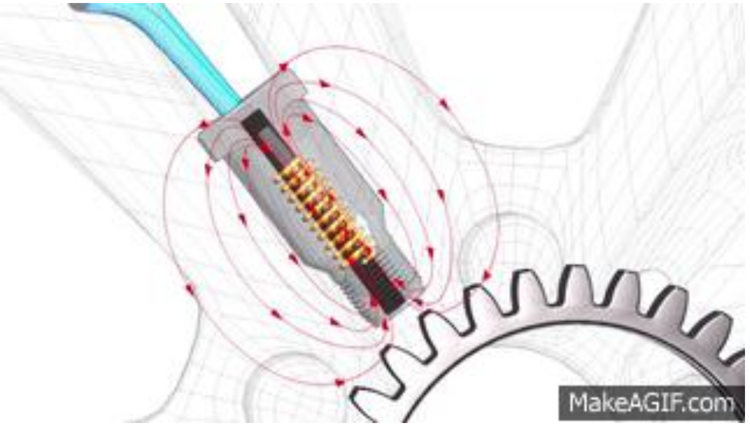
Principle

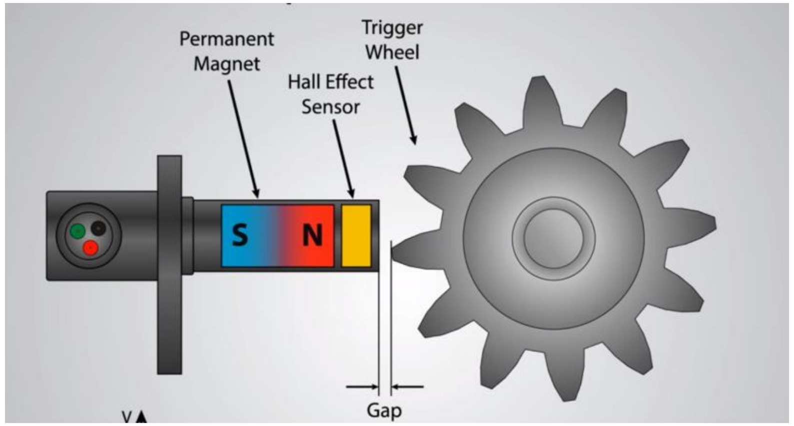
- Detecting the rotation of a wheel to measure the vehicle's speed.

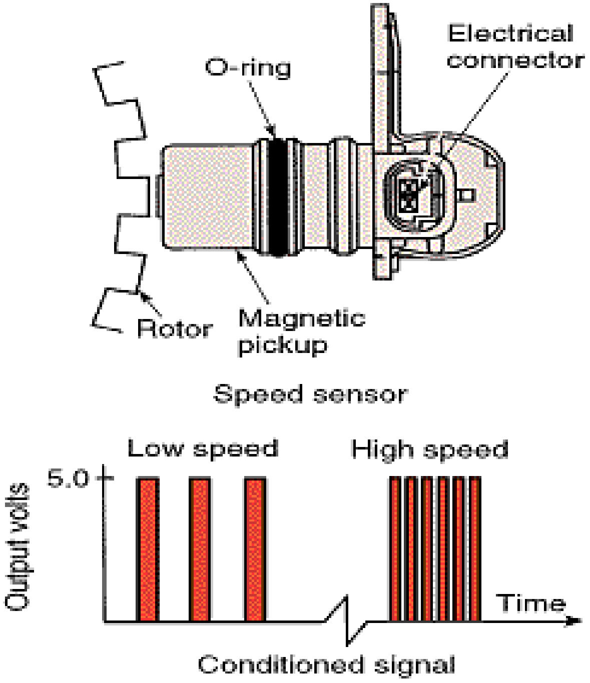
Process

1. Generating pulses with each rotation.
2. Using the number of pulses generated to track the wheel's rotation.

V: $speed\ of\ the\ vehicle$ $[m/s]$
r: $radius\ of\ the\ wheel$ $[m]$
ω: $wheel\ speed$ $[rad/s]$
N: $the\ number\ of\ pulses\ generated\ per\ unit\ time$
T: $measurement\ period$ $[s]$
Z: $pulses\ per\ revolution$







How to Count Speed Using Pulses?

- **Pulse counting method: speed measurement using pulses over a fixed period.**
  - Measuring the speed by dividing the number of pulses occurring within a fixed time interval by the time, obtaining the average speed over that interval.

- **Pulse timing method: speed measurement using time intervals between pulses.**
  - Measuring the time between consecutive pulses and determining speed.

- **Hybrid method**
  - Selecting between **pulse counting** and **pulse timing**, the wheel encoder adapts dynamically based on the current speed, utilizing pulse counting for high speeds and pulse timing for low speeds.

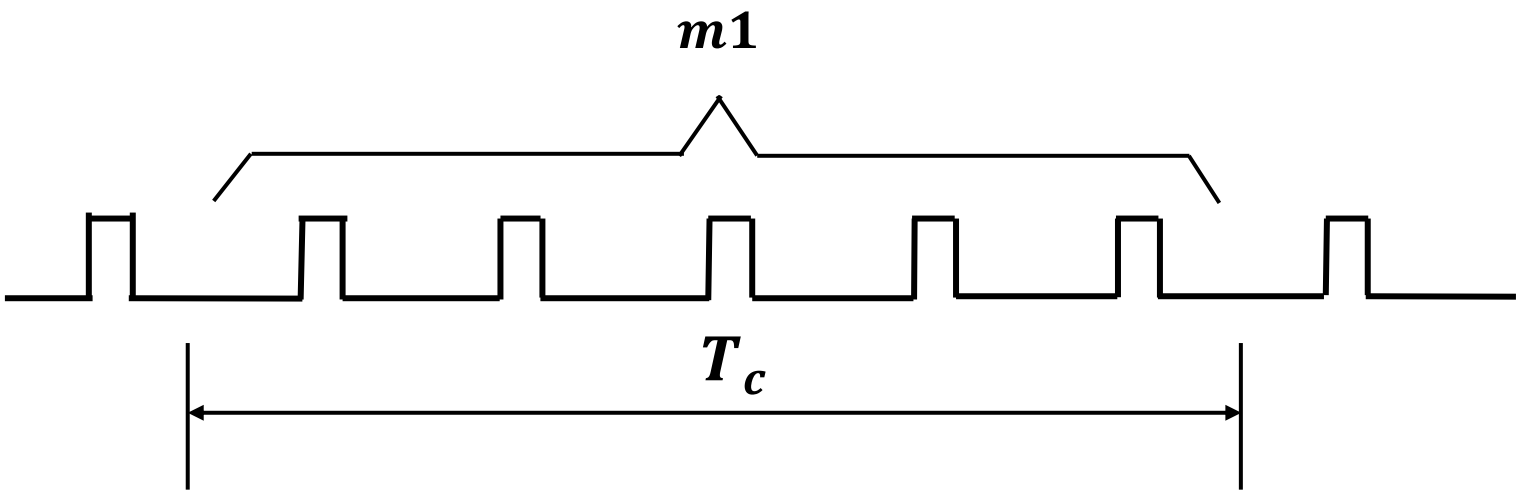
Pulse Counting Method

- **Speed measurement using pulses over a fixed time period (M Method).**
  - **Pros:** simple and allows for accurate speed estimation.
  - **Cons:** accuracy may decrease at low speeds.

ω_m : *angular velocity* [rad/s]
m_1 : *number of pulse*
T_c : *sampling period* [sec]
Z : *pulses per revolution*

measurement

Encoder pulse

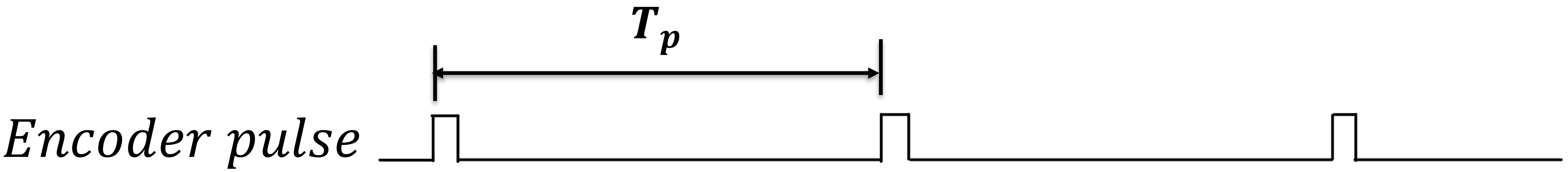


Pulse Timing Method

- **Speed measurement using time intervals between pulses (T Method).**
  - **Pros:** allows accurate distance or rotation calculation, and stable operation at low speeds.
  - **Cons:** difficult to achieve accurate speed measurement until the set pulse count is reached.

ω_m: *angular velocity* [rad/s]
Z: *pulses per revolution*
T_p: *prioud between pulse* [*sec*]

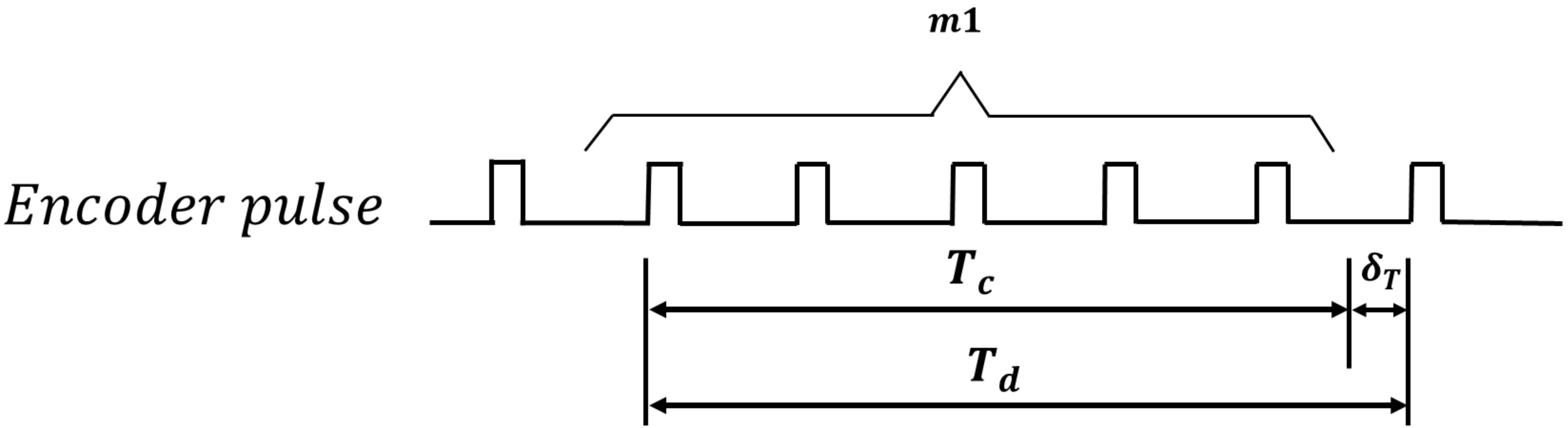
measurement



Hybrid Method

- **Pulse counting is used and the errors that occur at the end are reduced using the pulse timing.**
  - **Pros:** accurate speed measurement across a wide range of speeds.
  - **Cons:** requires a more complex algorithm and additional implementation.

ω_m: *angular velocity*
m_1: *M method number of pulses*
T_c: *m method counting period*
δ_T: *t method inter – pulse period*
T_d: *total downtime* $T_C + \delta T$
Z: *pulses per revolution*



Inertial Measurement Unit (IMU)

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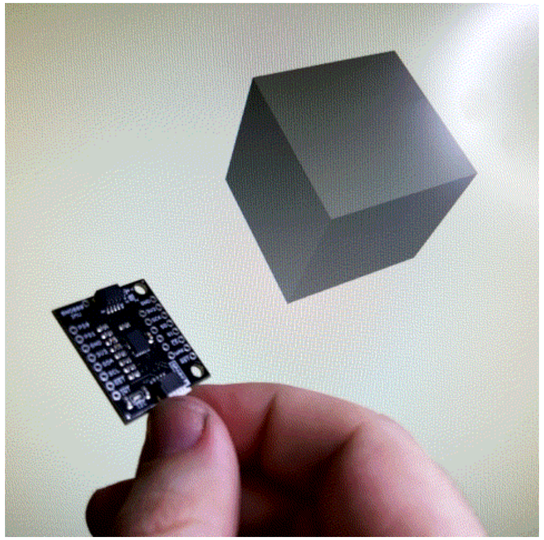
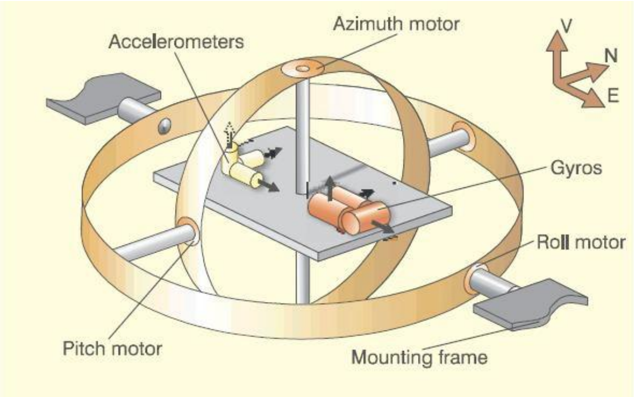
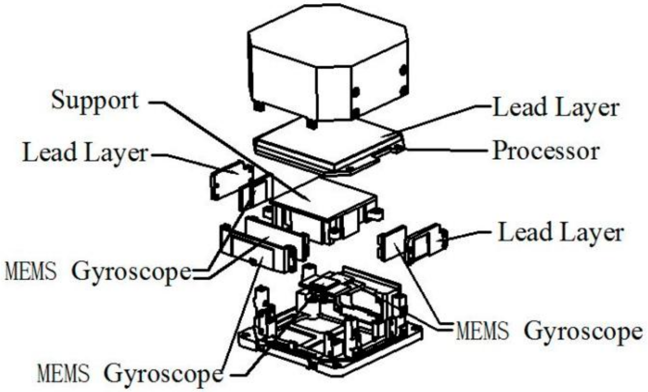


- **Electronic device that measures an object's acceleration, angular rate, and sometimes orientation.**
- **Using a combination of**
  - Accelerometers, Gyroscopes, (optional) Magnetometers.
- **Types of IMU**
  - Mechanical
  - Electronics (MEMS)
  - Optical



Mechanical - Gimbaled

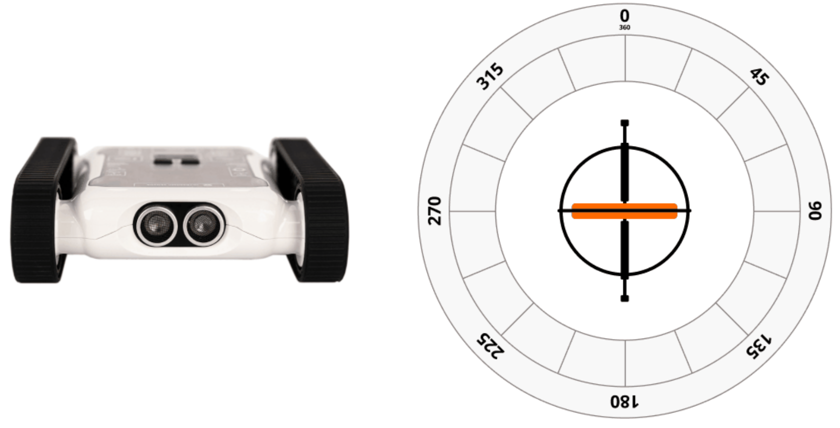


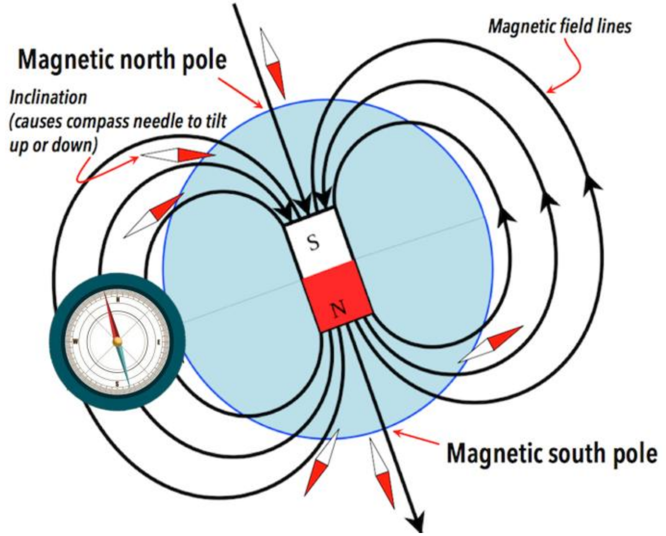
Electronics - MEMS

Optical - Ring laser gyroscope

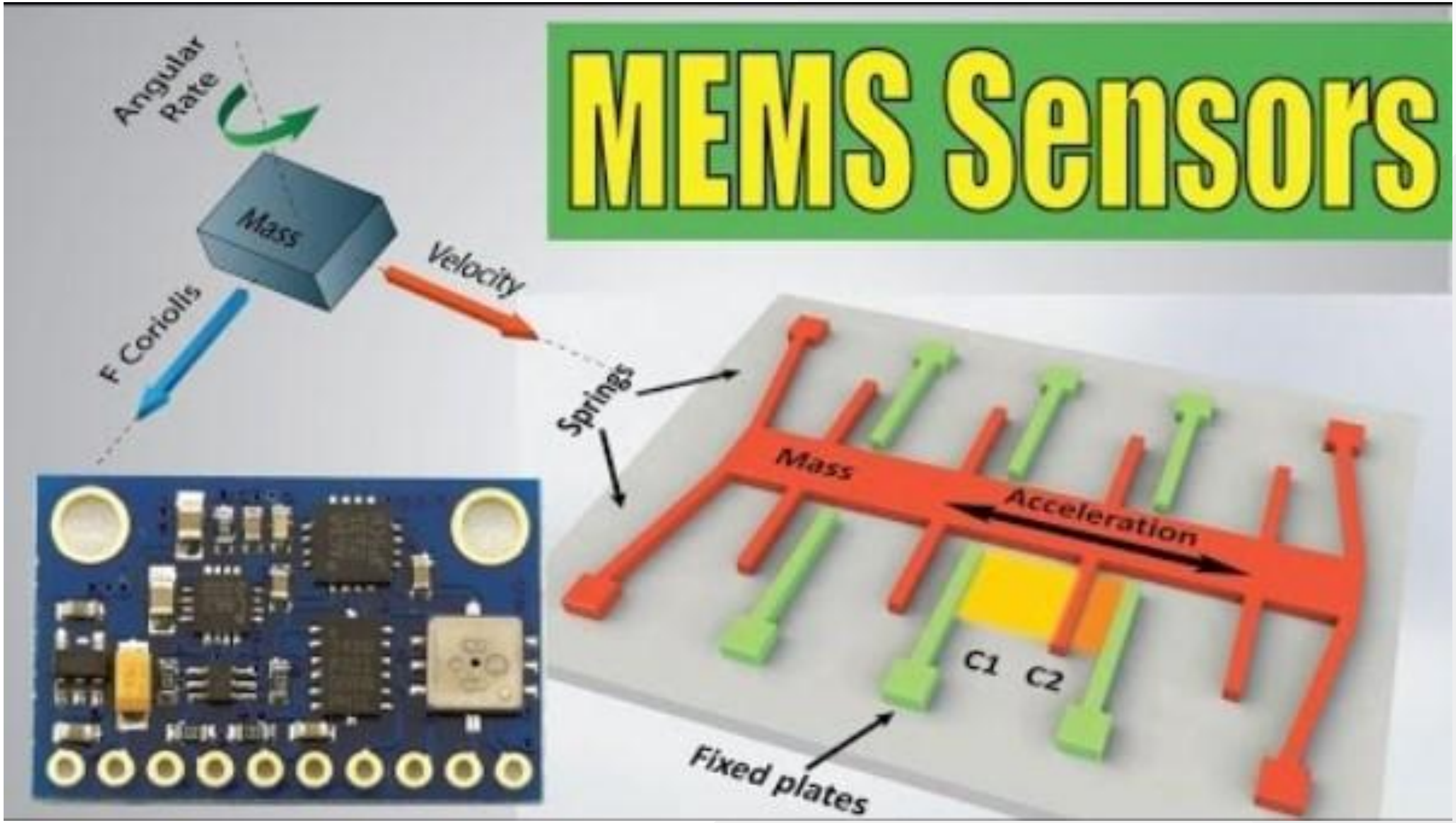
Components of IMU

- **Accelerometers**
  - The output includes the linear acceleration of the sensor and the gravitational acceleration of the Earth.
- **Gyroscopes**
  - The output includes the angular rate of the sensor and the rotation speed of the Earth.
- **(Optional) Magnetometers**
  - The input captures the Earth's magnetic field, and the output includes orientation information relative to the Earth's magnetic poles.

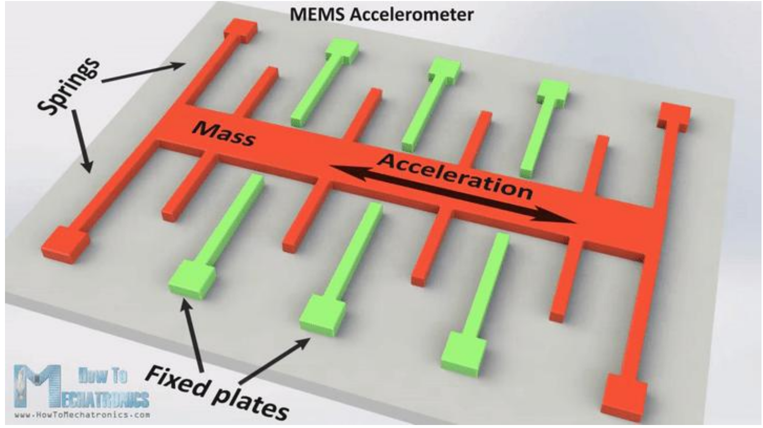




MEMS Gyroscope and Magnetometer



Principle of MEMS IMU



MEMS accelerometer

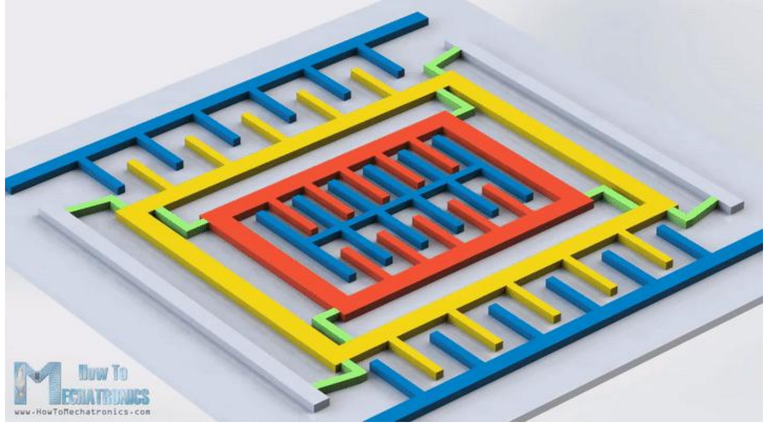
- It measures acceleration by measuring change in capacitance.

$$C_1 = \frac{\epsilon A}{d + \Delta d} \qquad C_2 = \frac{\epsilon A}{d - \Delta d} \qquad \Delta C = C_1 - C_2$$

$$V_{out} = K \Delta C$$

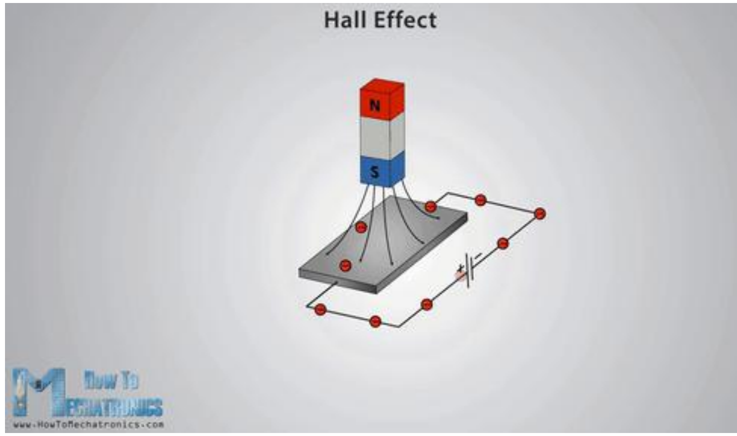
$$acceleration = \frac{V_{out}}{K'}$$

K': sensitivity coefficient
ϵ: permittivity
d: initial distance between the plates



MEMS gyroscope

- It measures rotational rate by using the Coriolis effect.
  - Vibrating mass in rotating system experiences a force perpendicular to the direction of rotation and its velocity.
  - This force changes sensor capacitance, which is converted into a voltage signal that reflect angular rate.



MEMS magnetometer

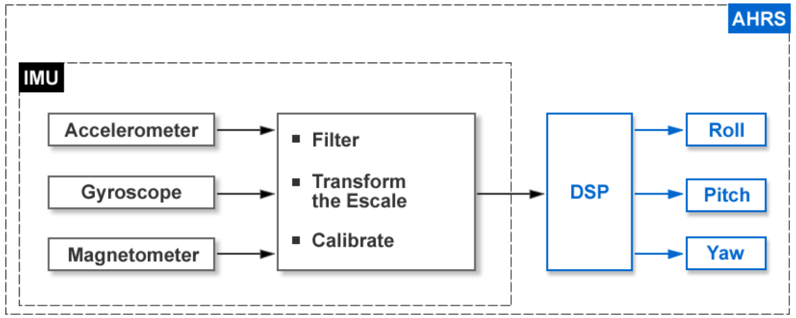
- It measures the earth magnetic field by using Hall Effect or Magneto Resistive Effect.

ARS & AHRS

- **IMU outputs, such as angular rate and acceleration, can be used to obtain object's attitude information.**

- **ARS**
  - ARS stands for **A**ttitude **R**eference **S**ystem.
  - It measures gravity with acceleration to calculate absolute roll and pitch.
  - It estimates change of yaw by accumulating angular rate.

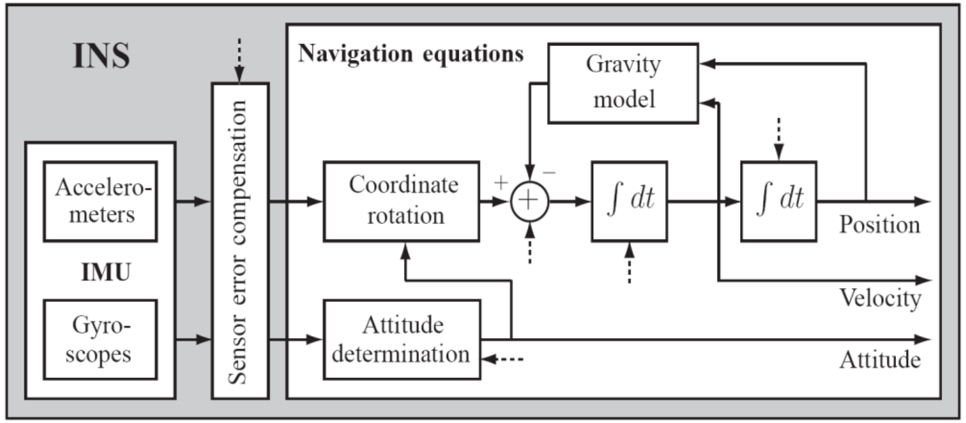
- **AHRS**
  - AHRS stands for **A**ttitude and **H**eading **R**eference **S**ystem.
  - It utilizes not only ARS but also magnetometer to measure the magnetic north.
  - Using this magnetic north, It determine absolute yaw, not only absolute roll and pitch.

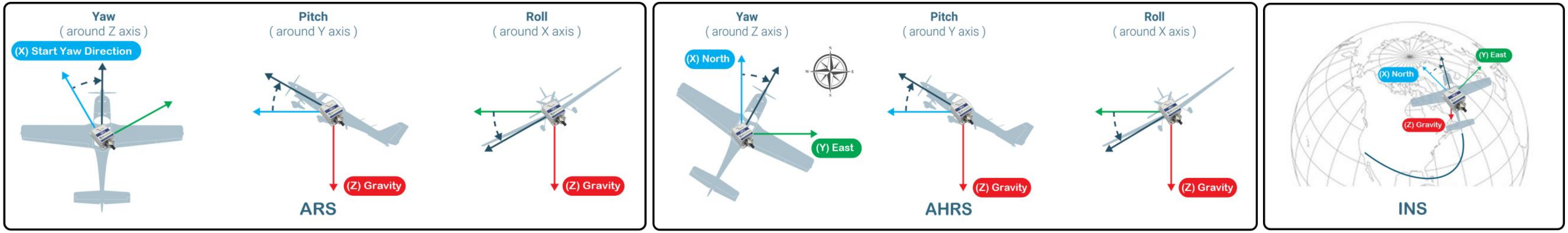


*DSP: Digital Signal Processor

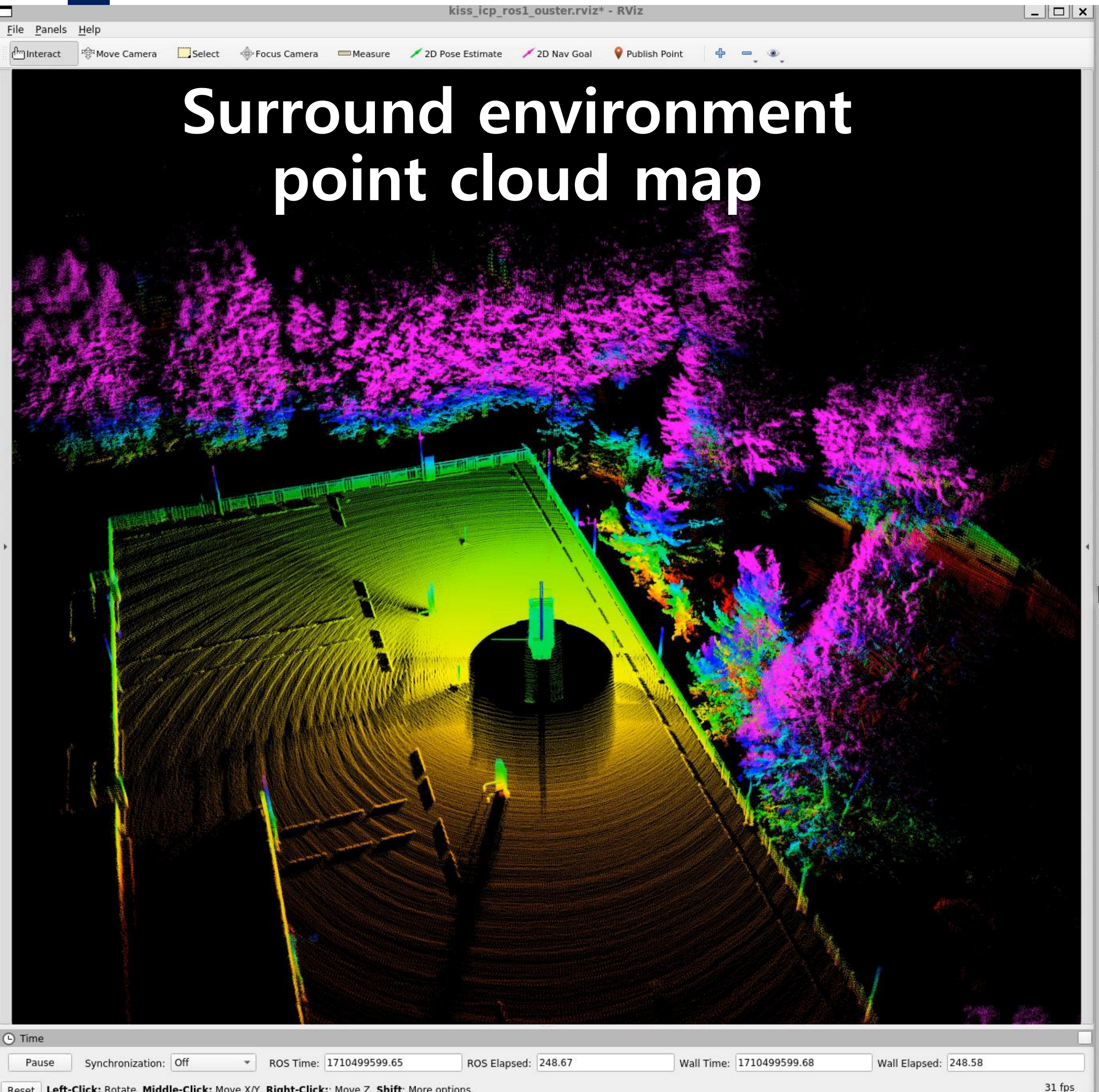
Inertial Navigation System (INS)

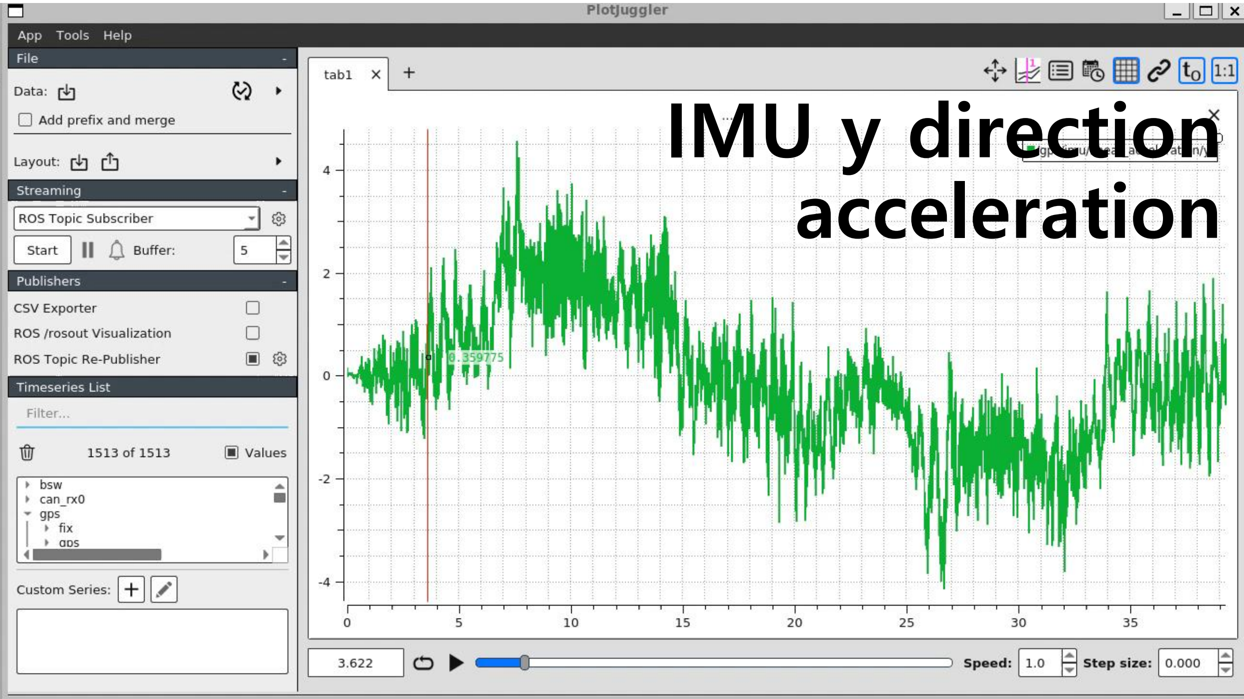
- **Use a high-precision gyroscopes and accelerometers to determine absolute position, velocity, and altitude based on initial position and velocity as well as acceleration and angular rate.**
- **Equipped with precise navigation algorithms, it can function without GPS signals.**
  - However, to compensate for drift error, it is often combined with external signals such as GPS.

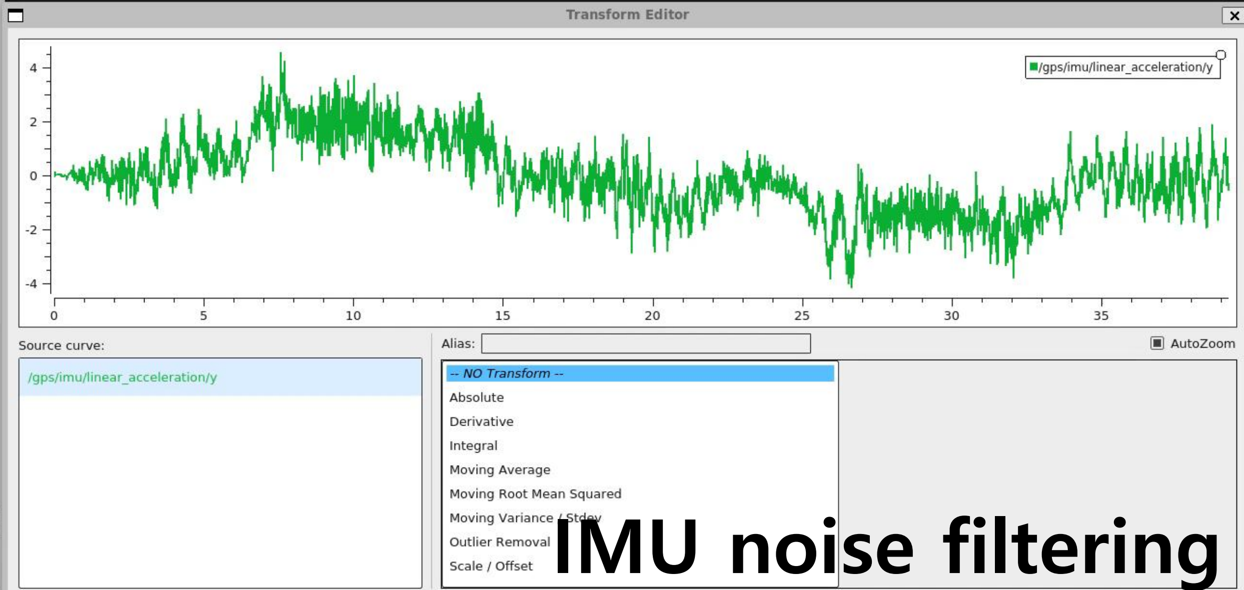




Real World IMU Measurement



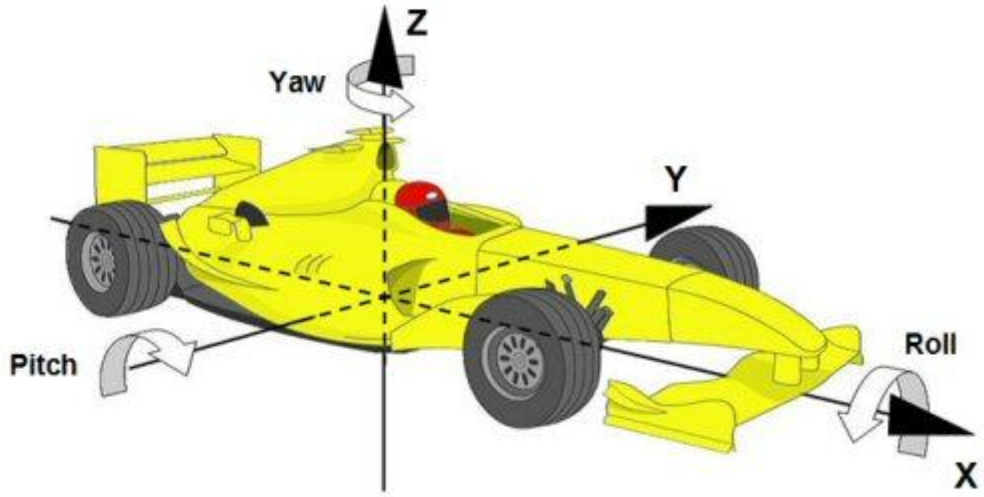




Electronic Stability Control (ESC)

Vehicle Motion

- **Vehicle coordinate system**
  - Fixed to the vehicle
  - Origin at the vehicle's center of gravity
  - X-axis in the longitudinal direction
  - Y-axis in the lateral direction
  - Z-axis in the vertical direction



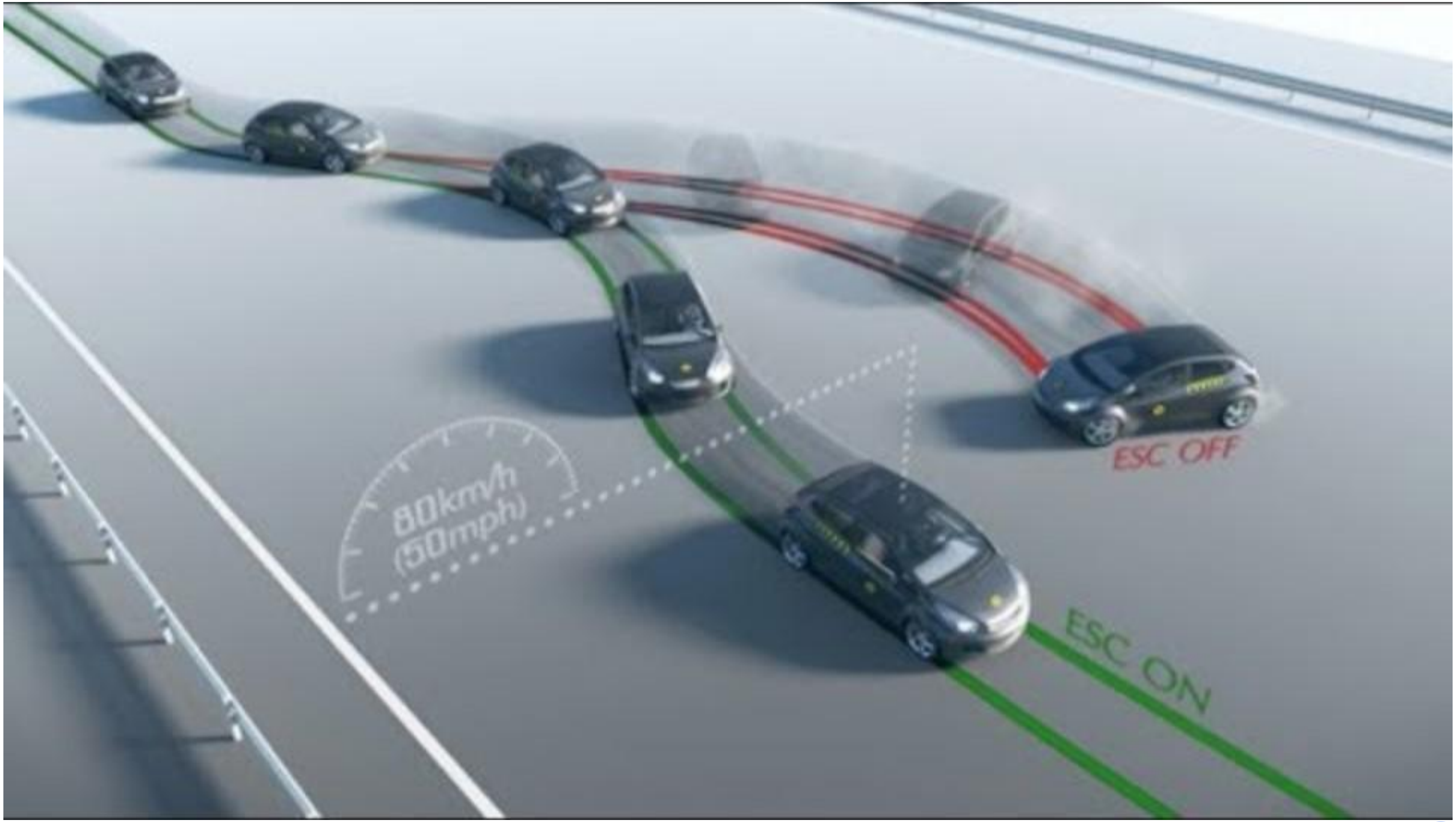
- **The vehicle motion has six independent degrees of freedom:**

1. Longitudinal motion in the x-direction
2. Lateral motion in the y-direction
3. Vertical motion in the z-direction
4. Rolling motion around the x-axis
5. Pitching motion around the y-axis
6. Yawing motion around the z-axis

Cause by

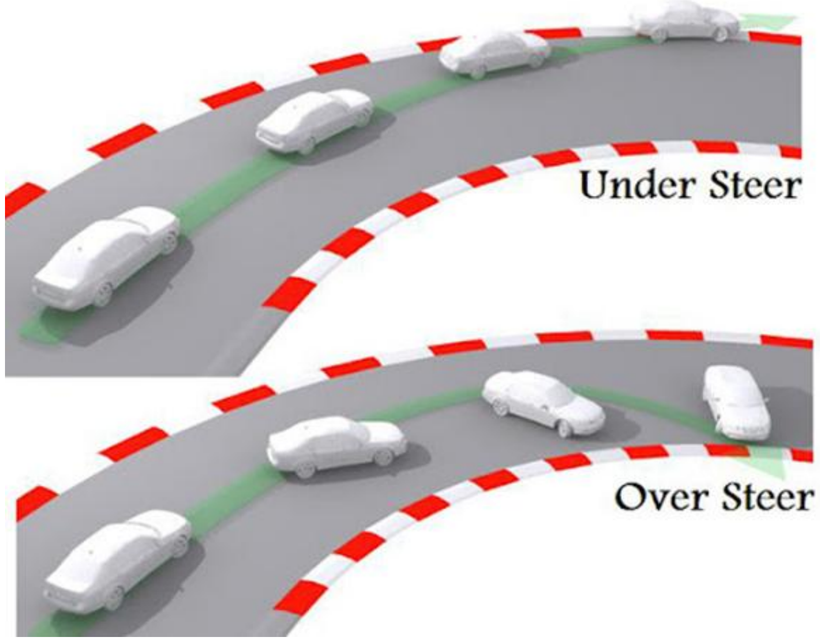
1. Acceleration and braking
2. Steering
3. Uneven road surface
4. Steering, road unevenness
5. Road unevenness, acceleration and braking
6. Steering

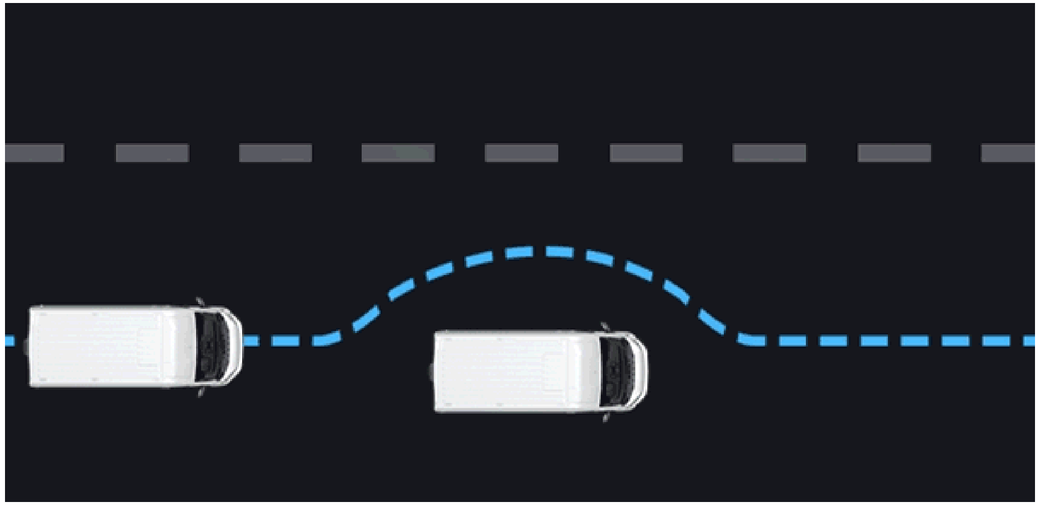
Electronic Stability Control

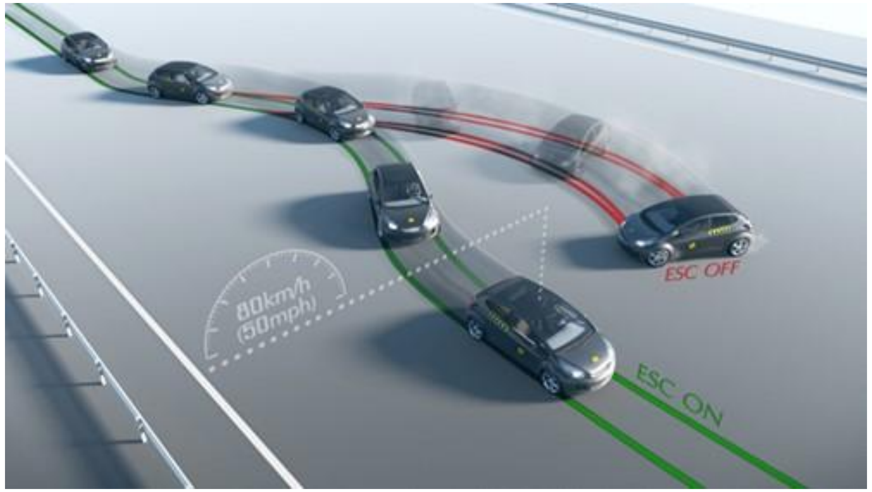


When is ESC Activated?

- **When it detects a probable loss of steering control.**
  - Loss of steering: driver's steering ≠ vehicle direction.
- **Understeer**
  - Vehicle turns less than driver's steering angle.
- **Oversteer**
  - Vehicle turns more than driver's steering angle.







Process of ESC

Process

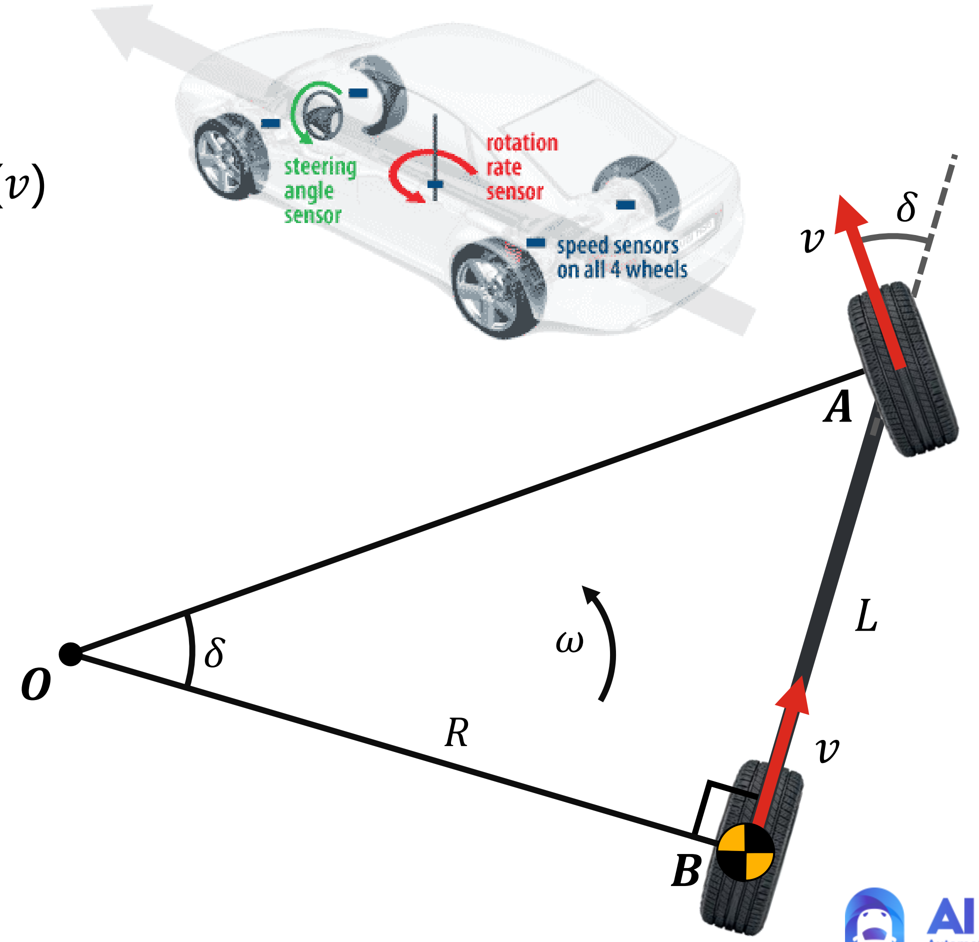
1. Compare the **target angular velocity** and **vehicle angular velocity**.
2. If the difference is large, control specific wheels or adjust engine output.

Target angular velocity

- Direction of driver's intention.
- Determined with steering angle (δ) and wheel speed (v)
-
  - $\boldsymbol{\omega = target\ angular\ velocity}$
  - $V = vehicle\ speed$
  - $\delta = steering\ angle$
  - $L = wheel\ base$

Vehicle angular velocity

- Measured yaw rate of the vehicle.



Sensors for ESC

Wheel Encoder

- Measure the wheel speed.

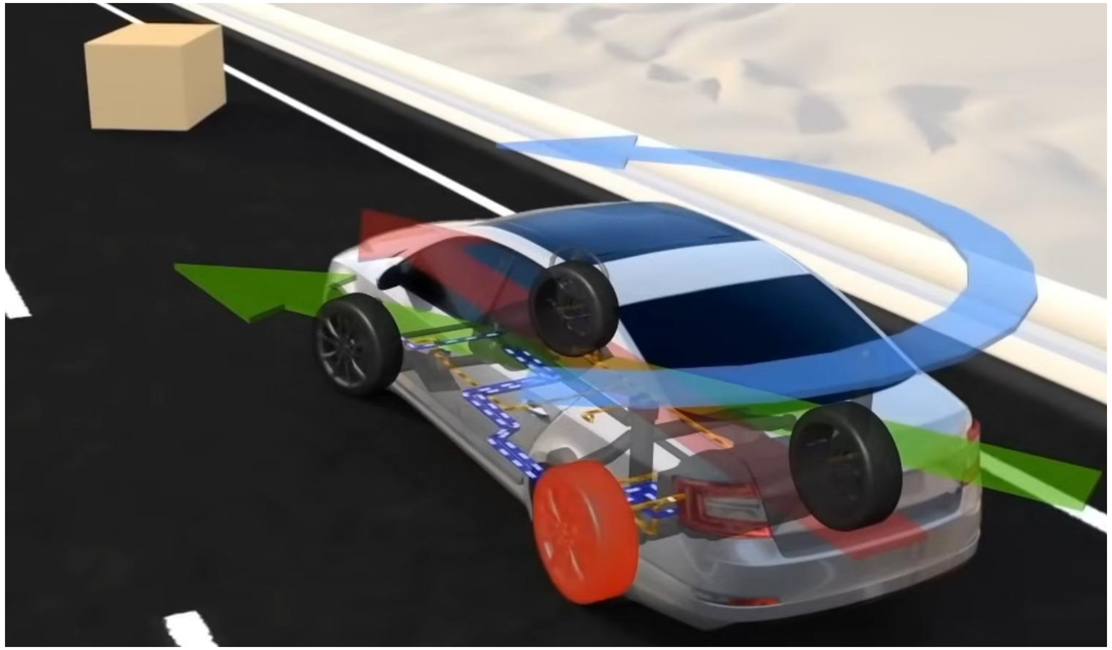
IMU

- Measure vehicle acceleration and angular velocity.

ESC process with sensors

- 1. Measure the **IMU** angular velocity (ω_{imu}) and determine target angular velocity (ω_{target}) with **wheel encoder** and **steering angle**.

- 2. Detect the difference IMU angular velocity (ω_{imu}) and target angular velocity (ω_{target}) and control the wheels**.**

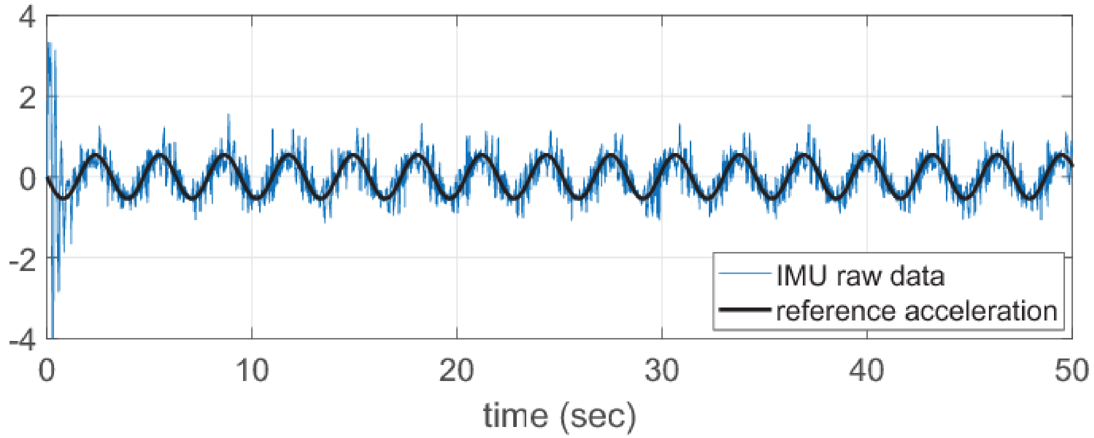


Noise Filtering

Noise

- **Anything that differs even slightly from the “real signal”.**

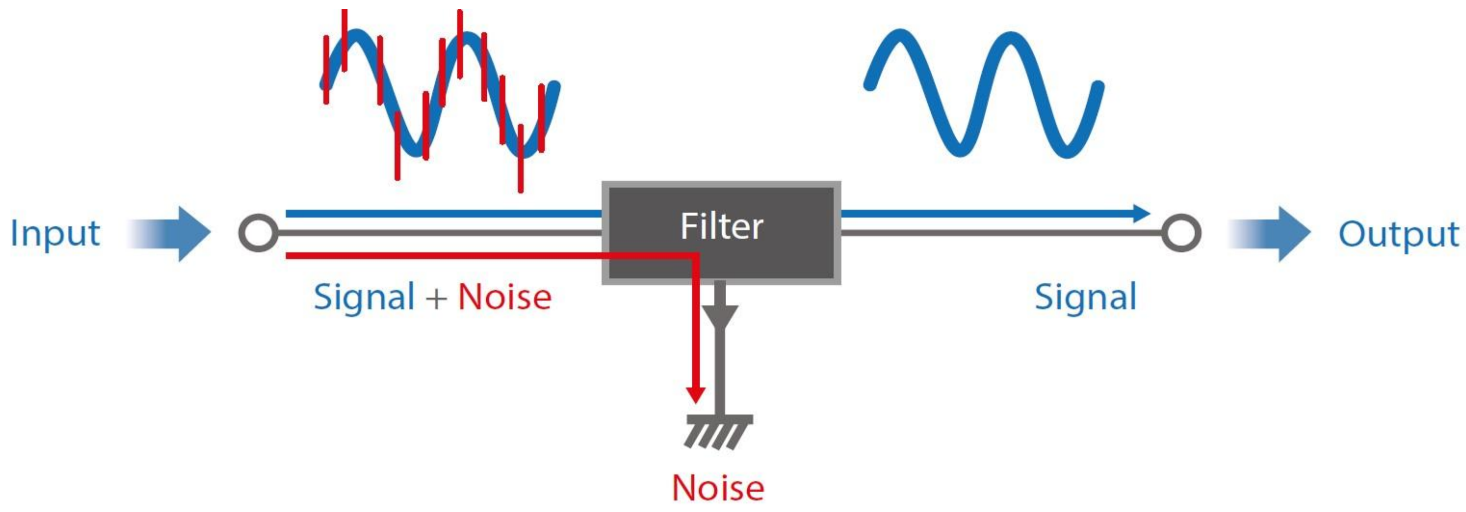
- **What makes noise?**
  - Temperature changes
  - Humidity
  - Mechanical vibration
  - Light interference
  - Manufacturing irregularities
  - Aging of components
  - …



Filtering (Static Filtering)

- **Technology to replace with relatively accurate sensor values.**

- **Types of filtering**
  - Average filtering
  - Moving average filtering
  - Exponential moving average filtering



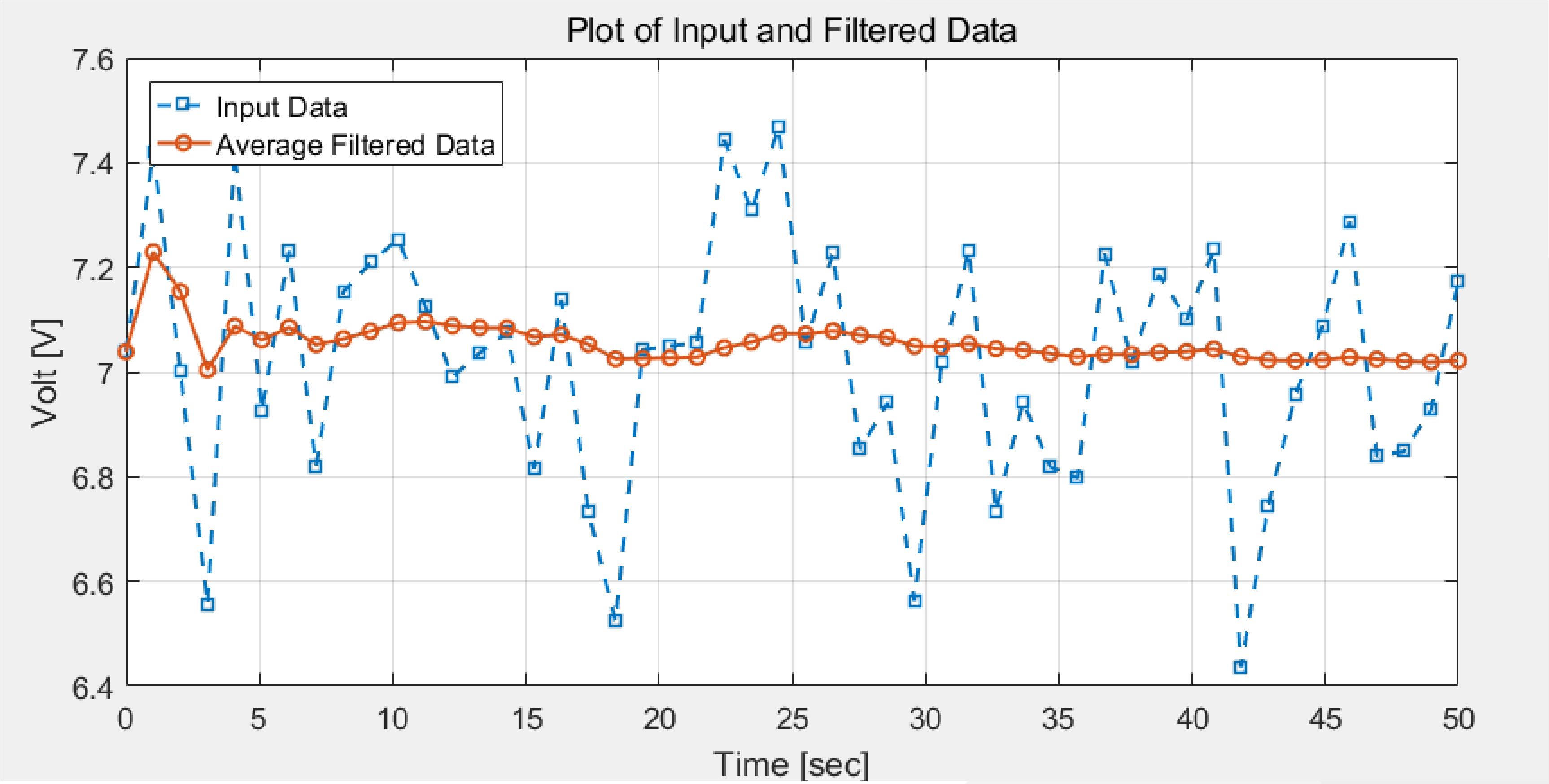
Average Filter

- **Divides the sum of all data by the number of data.**
  - $\bar{x}_k = \frac{x_1+x_2+\cdots+x_k}{k}$ $(x = data,\ k = number\ of\ data)$

- **Recursive expression**
  - Calculate a new mean using the previously calculated mean.
  - $\bar{x}_k = \boxed{} \left(= \frac{k-1}{k} \times \frac{x_1+x_2+\cdots+x_{k-1}}{k-1} + \frac{x_k}{k}\right)$

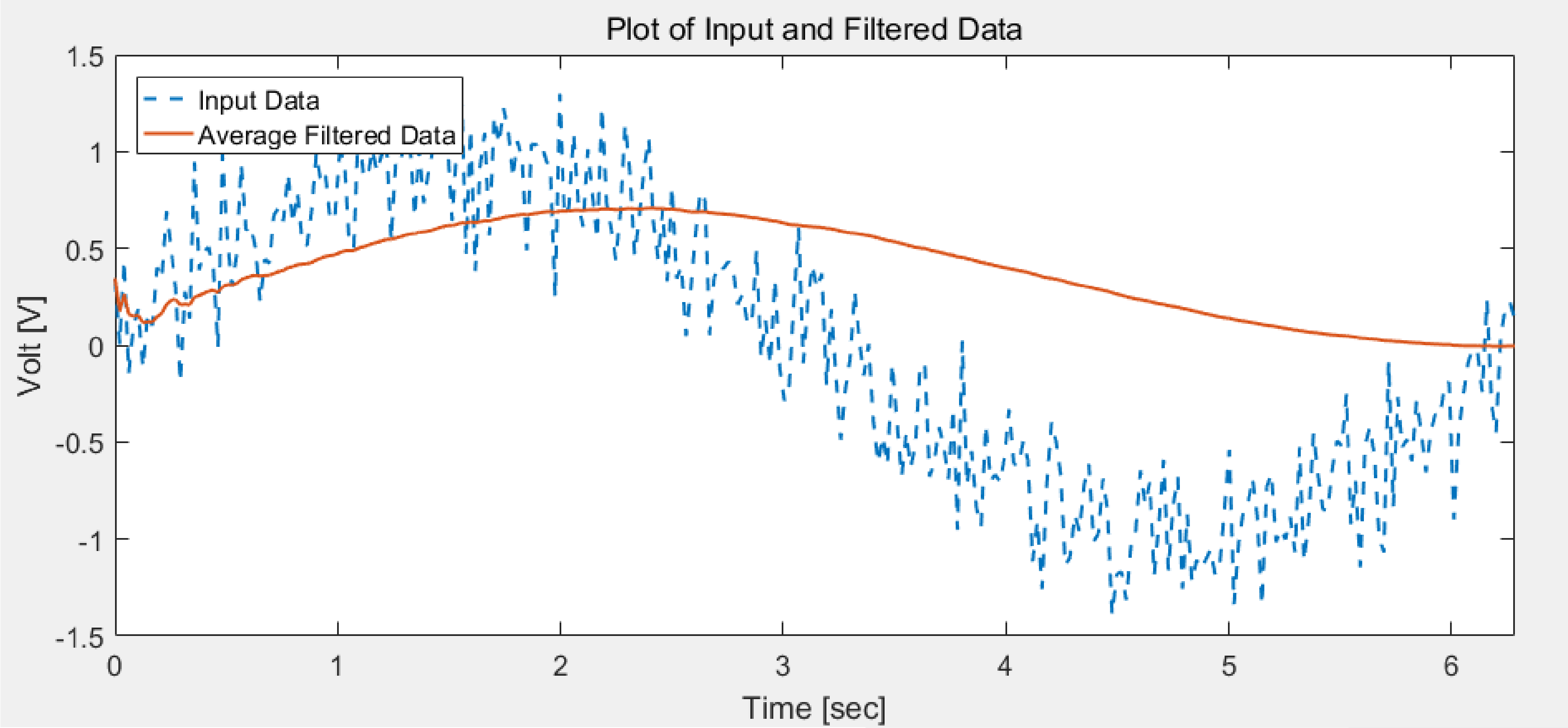
- **Ex1) When measuring a battery voltage of 7 volts every 1 second, the average voltage up to 11 seconds?**
  - $\bar{V}_{11} = \frac{V_1+V_2+\cdots+V_{10}+V_{11}}{11} = \boxed{}$

Average Filter



Average Filter

- Slow reactivity to changes in physical volume to be measured (low bandwidth).



Moving Average Filter

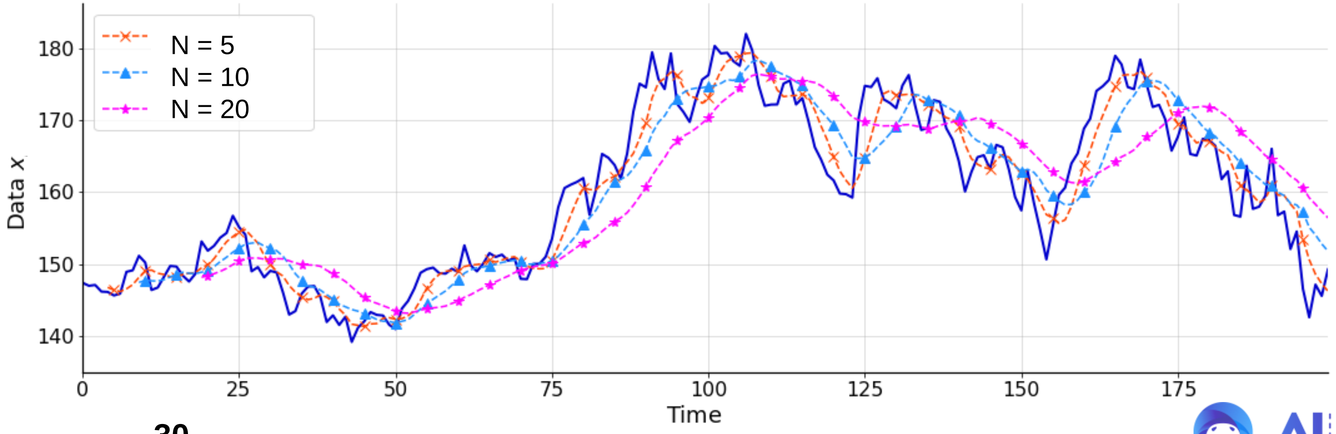
- **Mean calculated with the specified number of recent measurements (sliding window) only**
  - throw away the oldest data when new data comes in

$$\bar{x}_k = \frac{x_{k-n+1} + x_{k-n+2} + \cdots + x_k}{n} \qquad x = data, n = number\ of\ recent\ measurement$$

$$\bar{x}_k = \frac{x_{k-n} + x_{k-n+1} + \cdots + x_{k-1}}{n} + \frac{x_k - x_{k-n}}{n} = \boxed{}$$

- **Recursive expression exists but, x_{k-n} requires n data to be held.**
  - Inefficiency memory usage

- **Roles of sliding window**
  - As the **size** of the sliding window **increases**, it becomes **smoother**, but there is a **delay** in the result.



Exponential Moving Average Filter

Exponential Moving Average Filter

- Moving average filter that weighs exponentially lower with older measurements.

$$\bar{x}_{k-1} = \alpha \bar{x}_{k-2} + (1-\alpha) x_{k-1}$$

$$\bar{x}_k = \alpha(\alpha \bar{x}_{k-2} + (1-\alpha) x_{k-1}) + (1-\alpha) x_k$$

$$\bar{x}_k = \alpha^2 \bar{x}_{k-2} + \alpha(1-\alpha) x_{k-1} + (1-\alpha) x_k$$

$$\bar{x}_k = \alpha^k x_0 + \alpha^{k-1}(1-\alpha) x_1 + \cdots + \alpha^{k-n}(1-\alpha) x_n + \cdots + (1-\alpha) x_k$$

$$\alpha^{k-1}(1-\alpha) < \cdots < \alpha^{k-n}(1-\alpha) < \cdots < (1-\alpha)$$

1st Order Low pass filter

- **1st order Low pass filter has the same effect as exponential moving average filter.**

$$v_{in}(t) - Ri(t) = v_{out}(t)$$

$$Q_c = Cv_{out}(t)$$

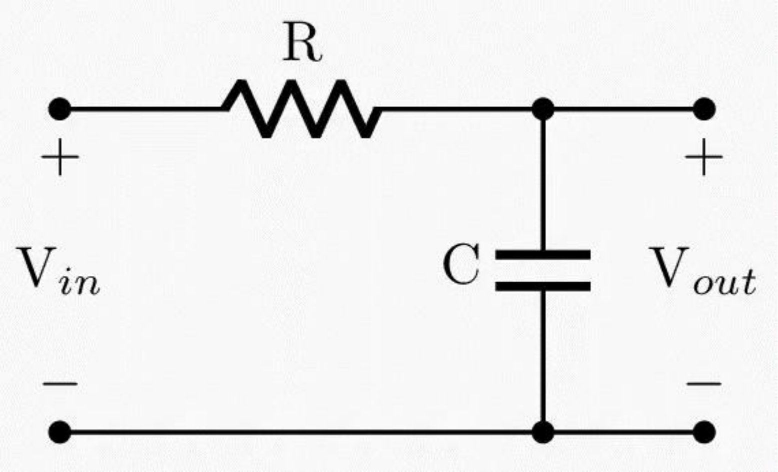
$$i(t) = \frac{dQ_c}{dt} = C\frac{dv_{out}(t)}{dt}$$

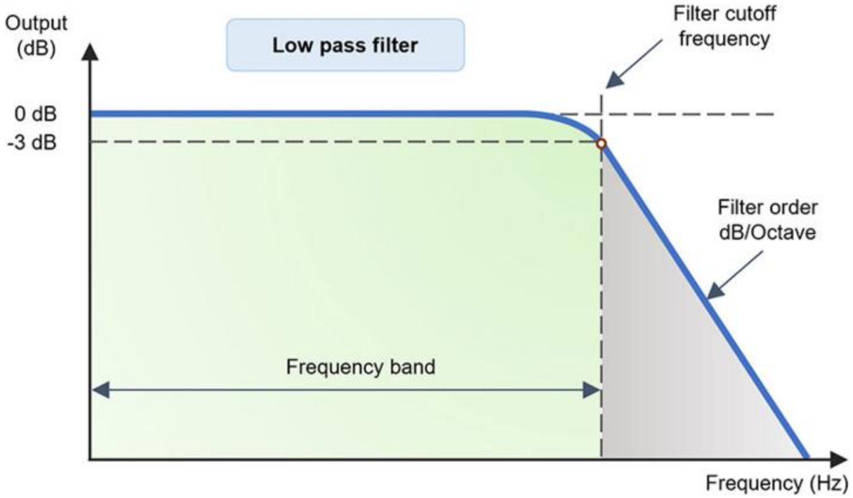
$$v_{in}(t) - v_{out}(t) = RC\frac{(dv_{out})}{dt}$$

$$x_k - y_k = RC\frac{y_k - y_{k-1}}{\Delta T}$$

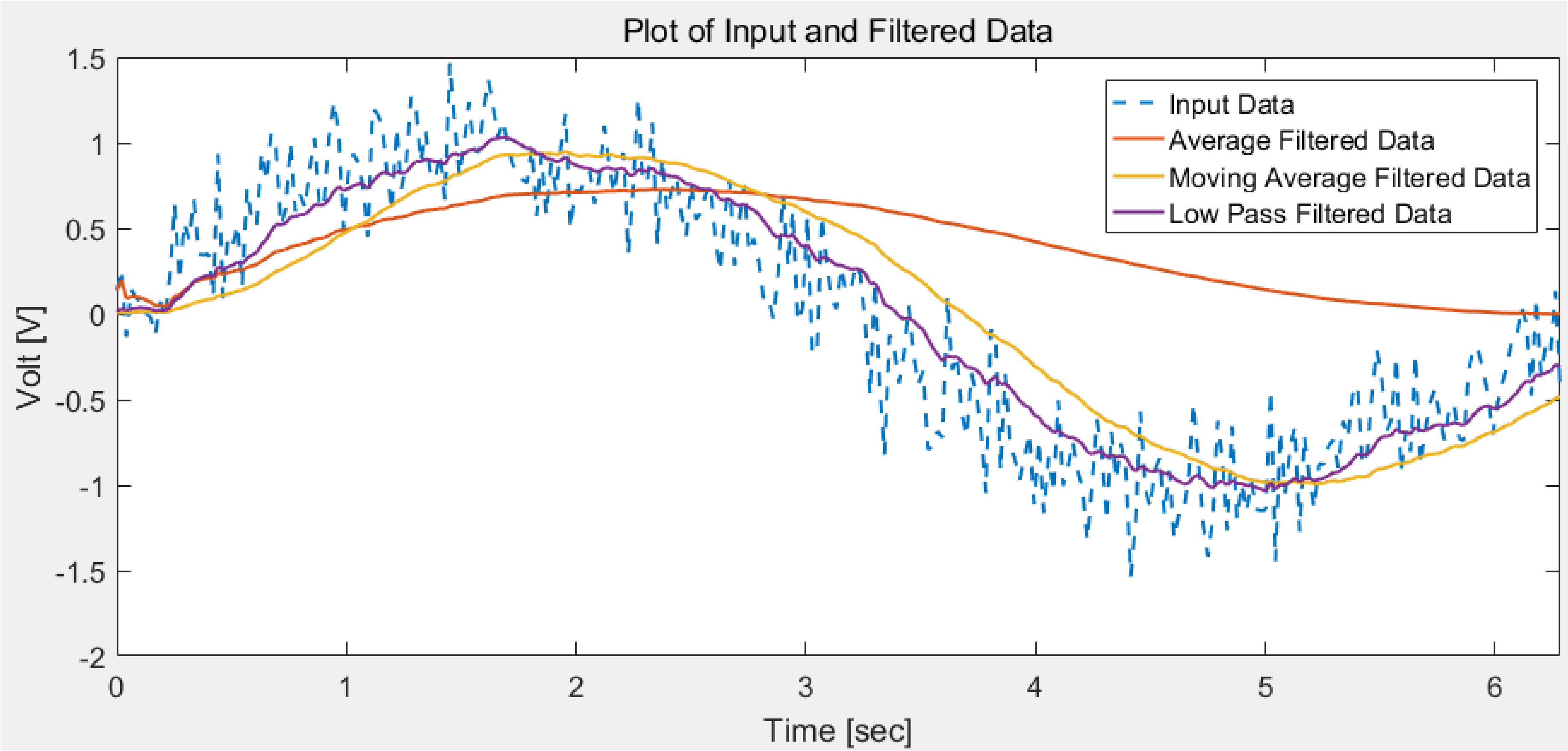
$$y_k = \left(\frac{RC}{RC + \Delta T}\right)y_{k-1} + \left(\frac{\Delta T}{RC + \Delta T}\right)x_k$$

$$y_k = \alpha y_{k-1} + (1-\alpha)x_k, \qquad \left(\alpha = \frac{RC}{RC + \Delta T}\right)$$





Exponential Moving Average Filter



THANK YOU
FOR YOUR ATTENTION