Transducers & Instrumentation

Module 01/01

(Measurement; Transducers; Sensors; Sensor Static Characteristics)

Measurement

- What is measurement?

A process of comparing an unknown quantity with a known or standard quantity.

- Different levels of measurements:
  - Nominal
  - Ordinal
  - Interval
  - Ratio

- In the physical science, we primarily use interval or ratio scales for measuring physical quantities.

Why measure?

- Gain information about an object of interest (scientific purpose).
- For the purpose of commerce.
- To influence or control the state of a system (engineering , medicine, etc.)

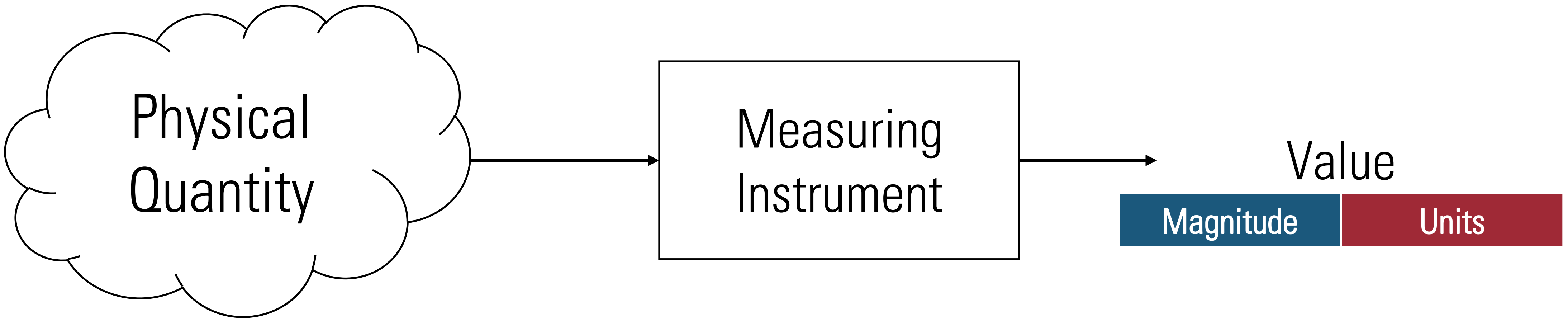
"To measure is to know."
"If you cannot measure it, you cannot improve it."
"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind."

\- Lord Kelvin

Measuring instrument

- What is measuring instrument?

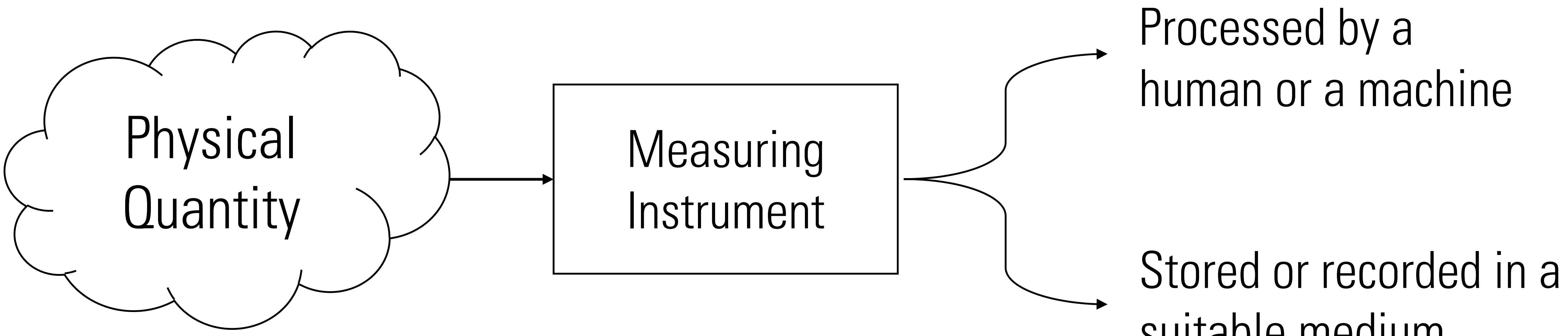
A device used to measure a physical quantity.



- A unit is definite magnitude of a physical quantity that is established as a standard.

Measuring instruments

- Fast and automatic measurements are essential for various applications.
- Modern day instruments measure a physical quantity by converting it into a signal that can be processed by a human observer/machine or be stored/recorded.



Transducers

- A device that converts energy from one form of energy to another from.

- General Transducers:
  - **Sensors**: Convert energy in one form to electrical energy. Produce signals that contain information about the *measurand*.

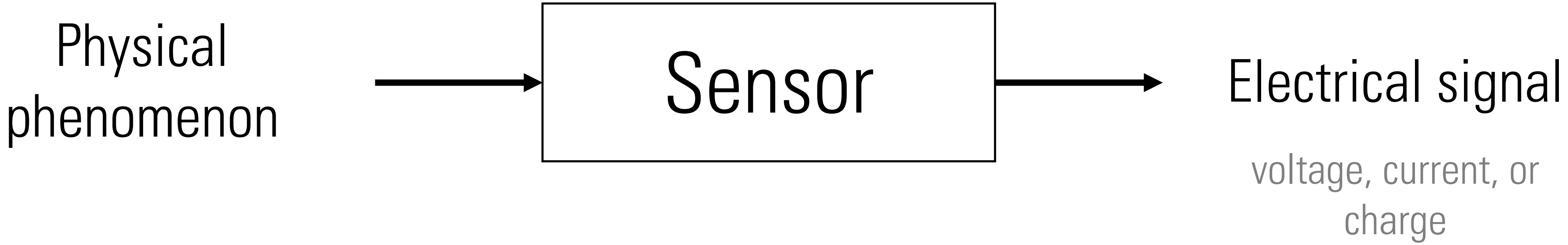
  - **Actuators**: Responsible for moving or controlling a system.

  - **Bidirectional transducers**: Transduce in both directions. Physical phenomenon to electrical energy and electrical energy to physical phenomenon.

Transducers

- Examples of transducers:

Sensors



- Measurand: Physical quantity, property or condition of interest.

E.g., motion, force, pressure, flow, temperature, biopotential, impedance, and chemical concentrations.

- Sensor output can be channelled, amplified, and modified by electronic circuits.

- The output signal can be described in terms of its amplitude, frequency, phase, and digital code.

Sensors Classification

- Direct vs. Complex
  - **Direct sensor**: Converts a stimulus directly into to an electrical signal.

  E.g., Piezoelectric sensor: mechanical energy is converted to electric charge displacement.

  - **Complex sensor**: Uses a cascade of transducers for energy conversion before employing a direct sensor at the end.

  E.g., A fibre optic displacement sensor.

Sensors Classification

- Passive vs. Active
  - **Passive**: Do not need additional source of energy to generate a signal in response to the measurand.

  E.g., Photodiode.

  - **Active**: Require external power supply for their operation – excitation signal, which is modified by the measurand.

  E.g., Resistive strain gauge.

Sensors Classification

- Absolute vs. Relative
  - **Absolute**: Measures with respect to an absolute physical scale.

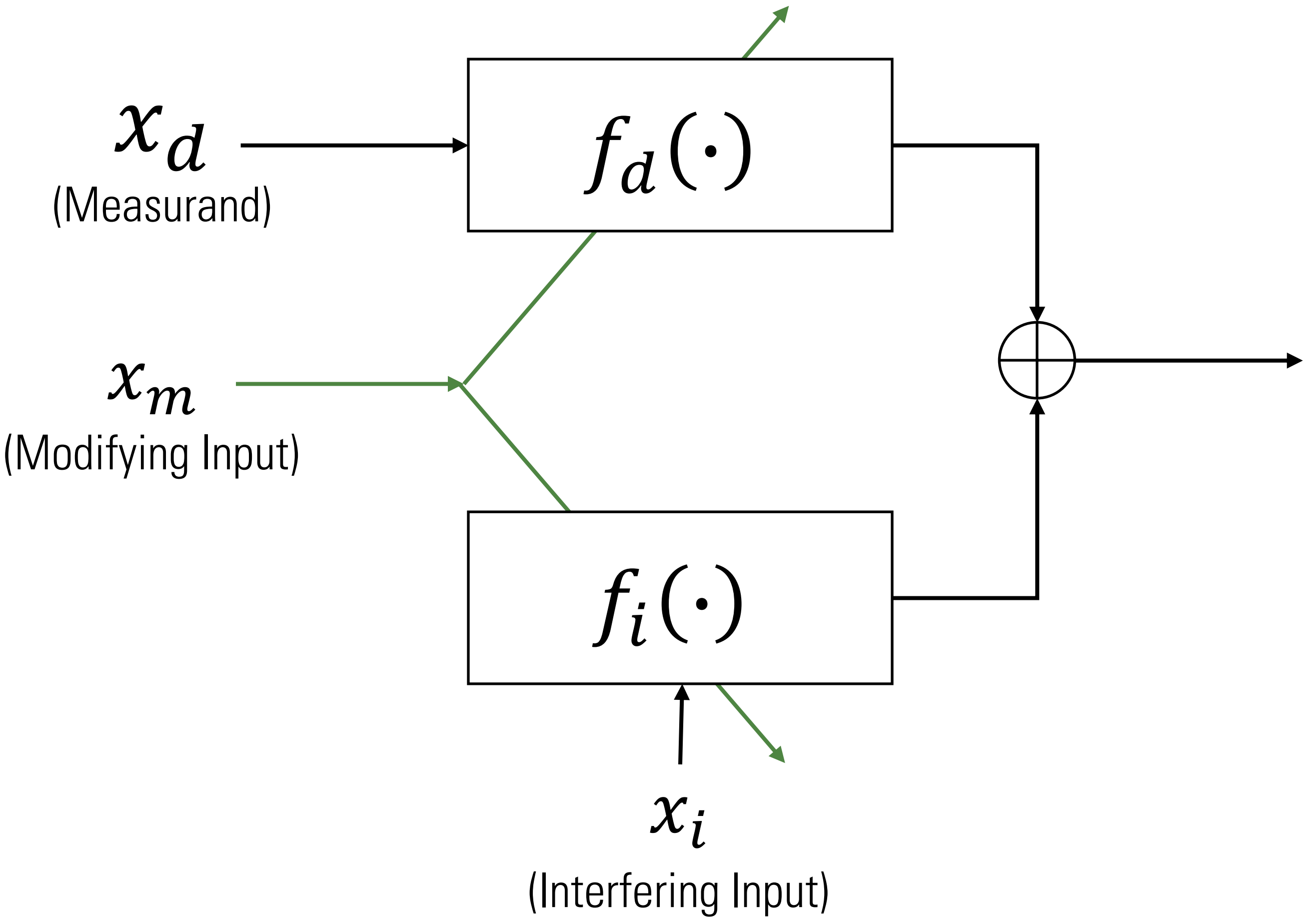
  E.g., Thermistor's resistance directly relates to the absolute temperature scale in Kelvins.

  - **Relative**: Measures with respect to a custom set reference.

  E.g., Thermocouple produces a voltage that is proportional to the temperature gradient between.

Sensor characteristics

- General Input-Output relationship of a Sensor.



$$y = y_d + y_i + \varepsilon$$

$$y_d = f_d(x_d, x_m)$$

$$y_i = f_i(x_i, x_m)$$

Sensor characteristics

- Examples of different types of inputs.

Manometer

Strain gauge

Methods for compensation

$$y = f_d(x_d, x_m) + f_i(x_i, x_m) + \varepsilon$$

- Design for inherent insensitivity
  - Design to minimise sensitivity to interfering $\left(\frac{\partial f_i}{\partial x_i}\right)$ and modifying inputs $\left(\frac{\partial f_d}{\partial x_m}, \frac{\partial f_i}{\partial x_m}\right)$.
- Feedback compensation
  - Use –ve feedback with high-gain to improve sensor characteristics.
- Filtering
  - Attenuating interfering and modifying inputs, or their effect on the output.
- Opposing inputs
  - Use of additional interfering inputs to cancel undesired output components.

Generalized sensor characteristics

- All sensors are non-linear dynamical systems.
  - Static and/or Linear approximations are often possible and very useful.

- General sensor characteristics are divided into static and dynamic characteristics.
  - **Static characteristics.** Response to constant or slow varying measurands.
  - **Dynamic characteristics.** Response to time varying measurands.

Static calibration

General input-output relationship for a constant input (x_d) :

$$y = f_d(x_d, x_m) + f_i(x_i, x_m) + \varepsilon$$

- All inputs are fixed, except one is kept at some constant value.
- We should be able to control these inputs.
- We must be able to measure the desired input with high accuracy.
- How do we know the input values of the measurand (desired input)?
  - Use a standard with known accuracy.
  - Standard is just another measuring device; has the highest possible accuracy level.
  - Rule of thumb: input must be measured with a standard having an accuracy at least 4 times better than the desired accuracy.

Static calibration

General Procedure:

1. Identify all possible inputs to the sensor and choose the desired inputs.
2. Get the necessary devices to vary all desired inputs over the necessary range. Use the appropriate standard for measuring the input levels.
3. Holding all other inputs constant, vary the desired inputs and record the output(s).
4. Develop the desired input-output model.

Static characteristics

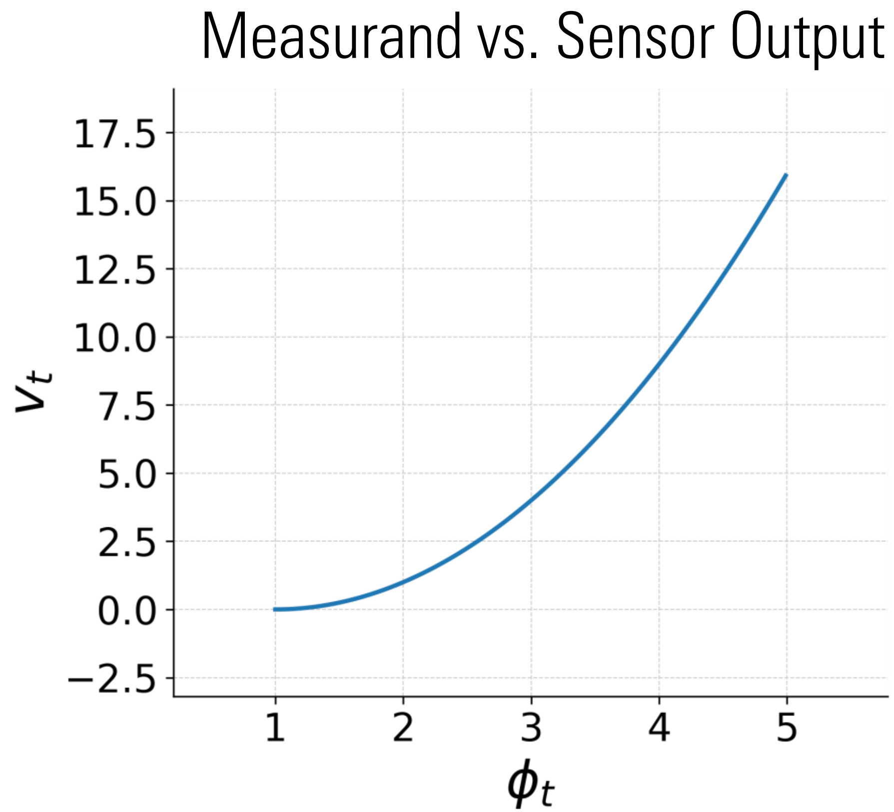
$$\varphi_t \longrightarrow \boxed{\text{Sensor}} \xrightarrow{v_t} \boxed{g(\cdot)} \longrightarrow \varphi_a$$

$$v_t = f(\varphi_t)$$

$$\varphi_a = g(v_t)$$

Under ideal conditions: $g = f^{-1}$

$$\varphi_a = g(v_t) = \varphi_t$$



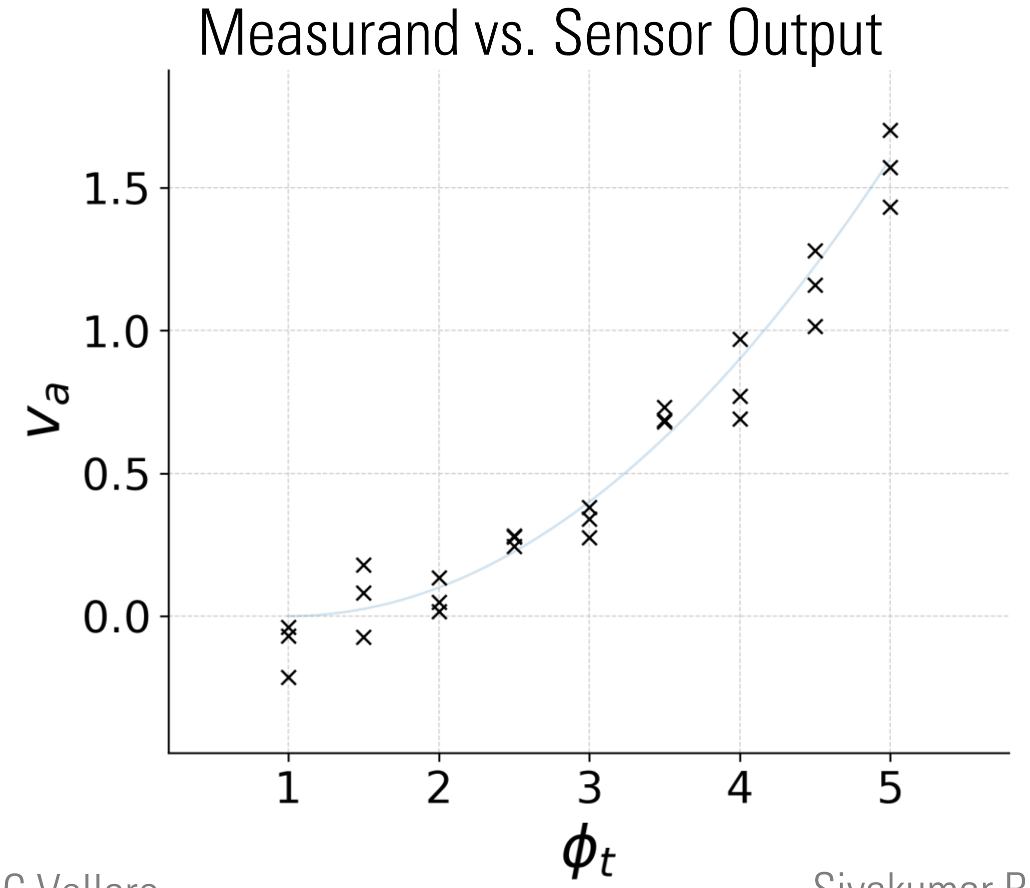
Static characteristics

$$\varphi_t \longrightarrow \boxed{\text{Sensor}} \xrightarrow{v_a} \boxed{g(\cdot)} \longrightarrow \varphi_a$$

In reality,

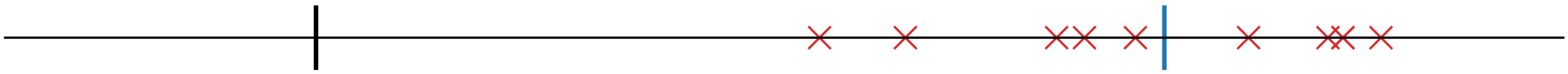
$$v_a = v_t + \varepsilon$$

$$(v_t = f(\varphi_t))$$



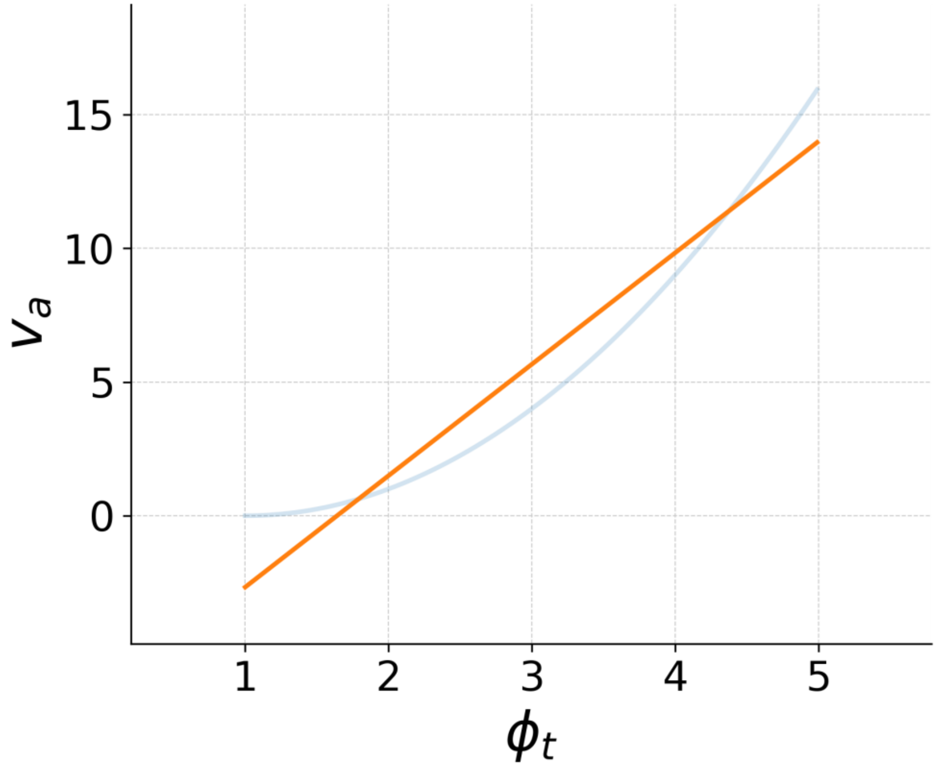
Sensor characteristics – Systematic & Random Errors

- Repeated measurements for a fixed value of the measurand.



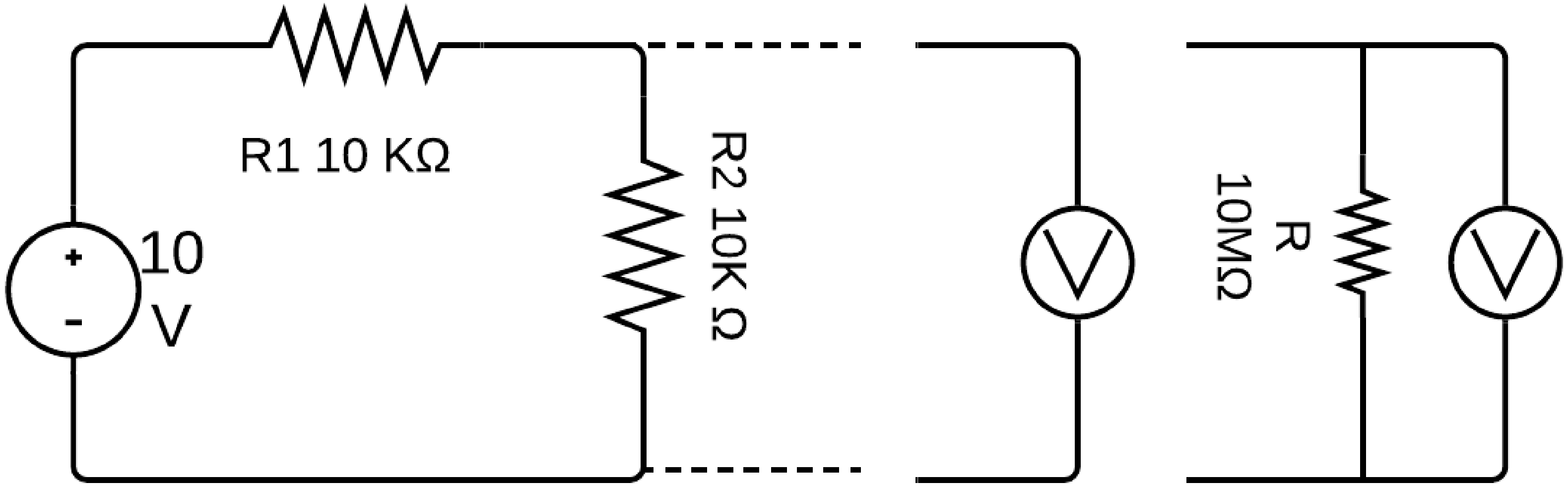
Sensor characteristics: Sources of Systematic Error

- **Errors in calibration**: Mistake in the chosen model.



Sensor characteristics: Sources of Systematic Error

- **Loading effects:** The measurement system affects the measurand.



Sensor characteristics: Sources of Systematic Error

- **Effect of other variables:** Effect of some unaccounted variable.

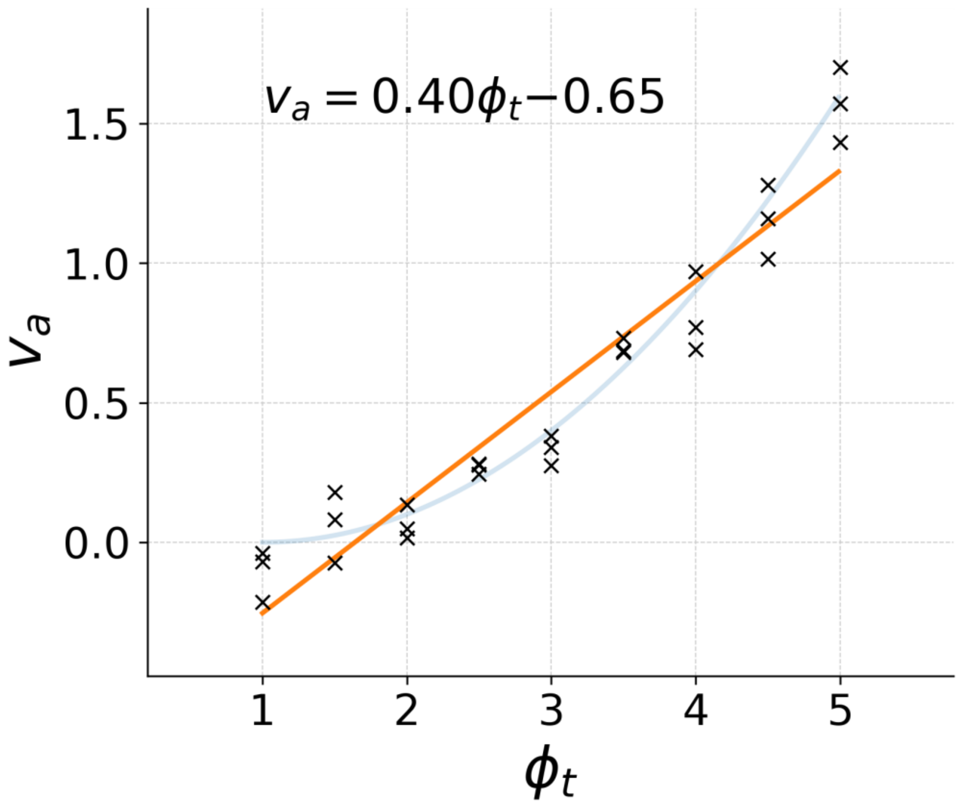
Sensor characteristics: Sources of Random Error

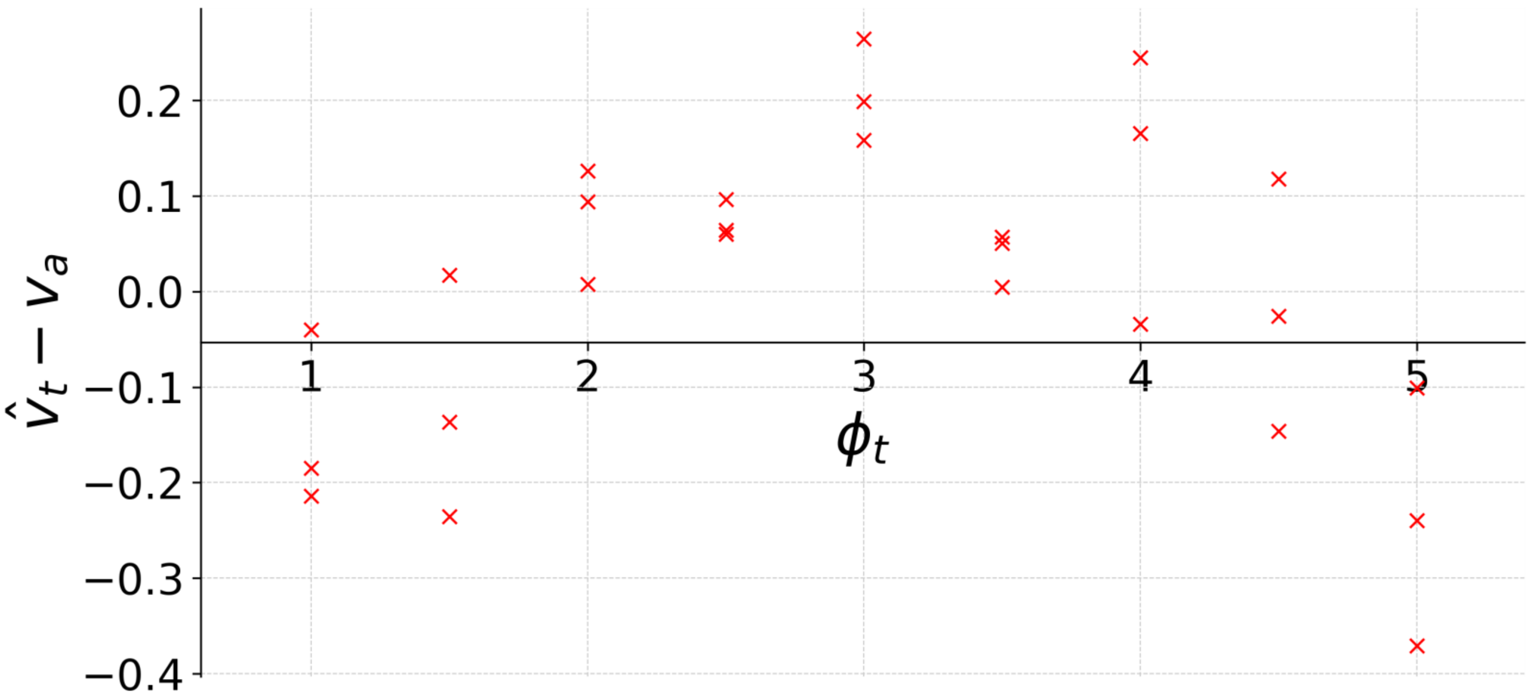
- Arise from the measurement system, the experimental system, and the environment.

Static characteristics

$$\varphi_t \longrightarrow \boxed{\text{Sensor}} \xrightarrow{v_a} \boxed{g(\cdot)} \longrightarrow \varphi_a$$

$$v_a = v_t + \varepsilon$$
$$\left(v_t = f(\varphi_t)\right)$$





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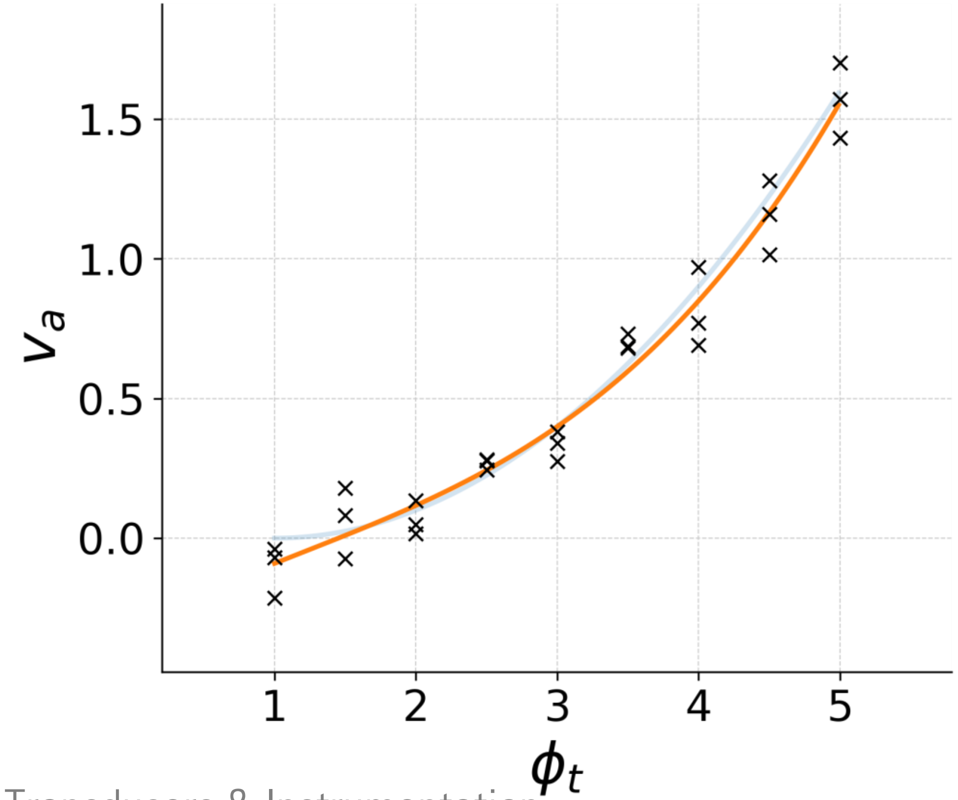
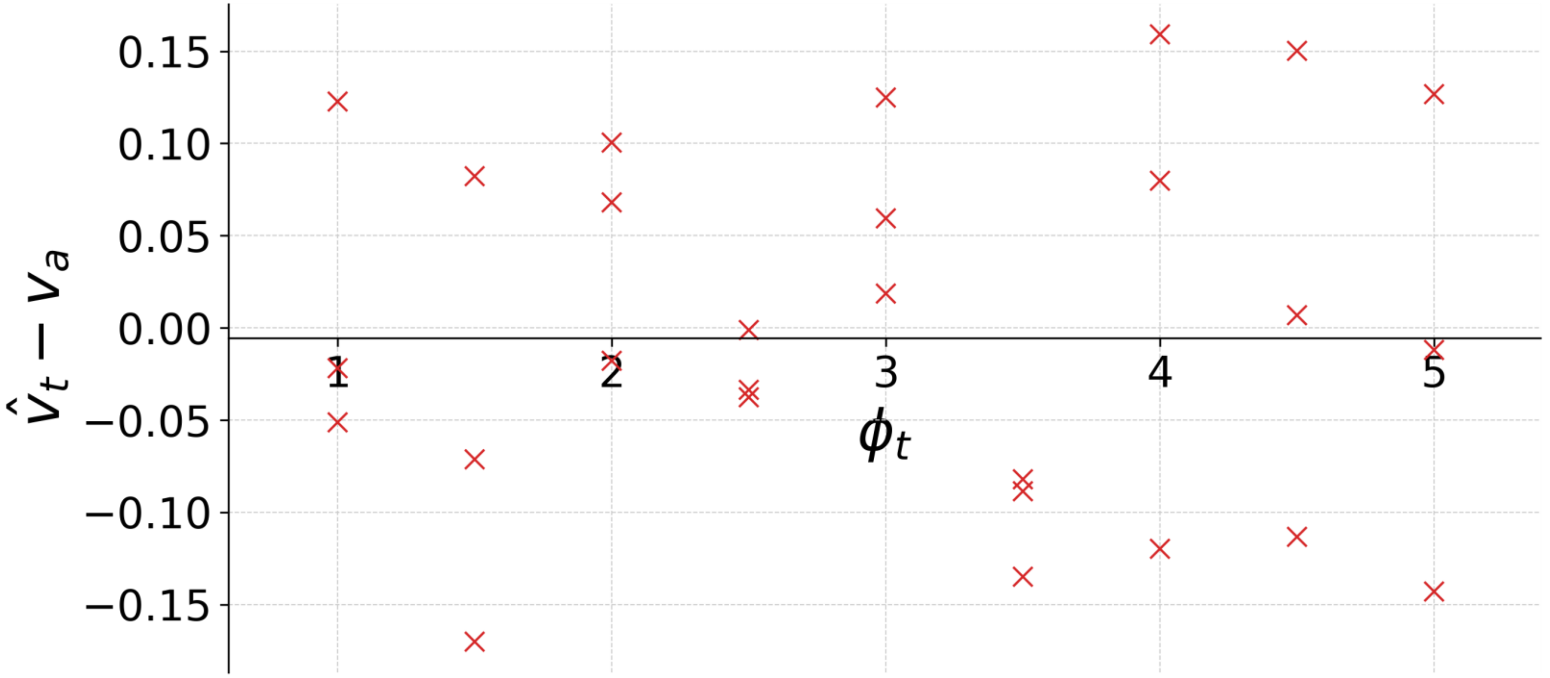
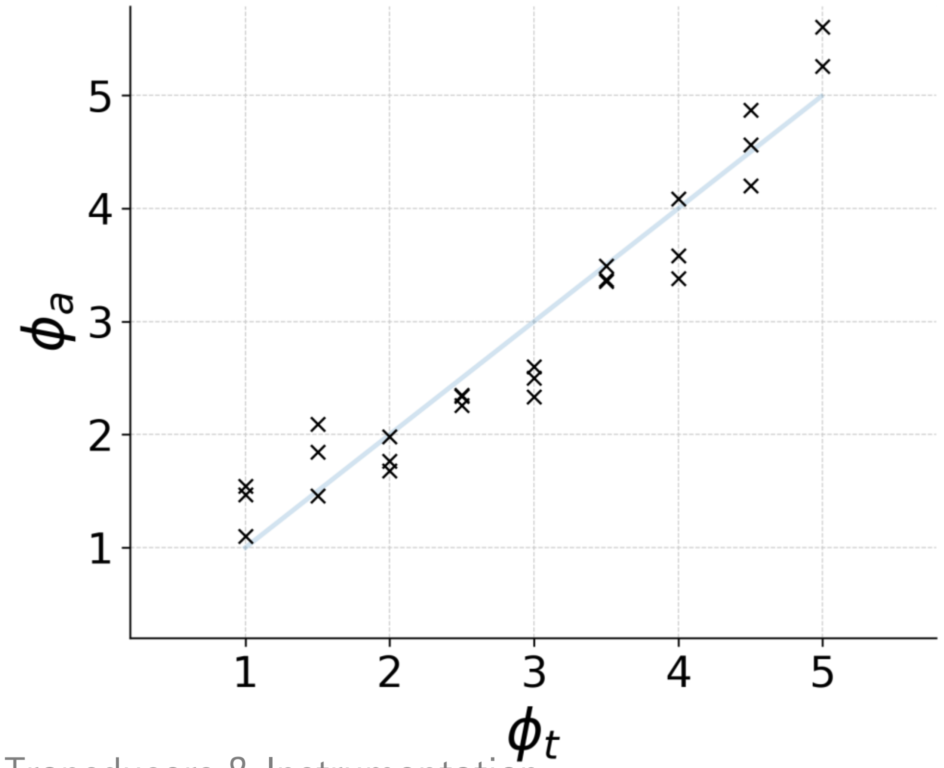


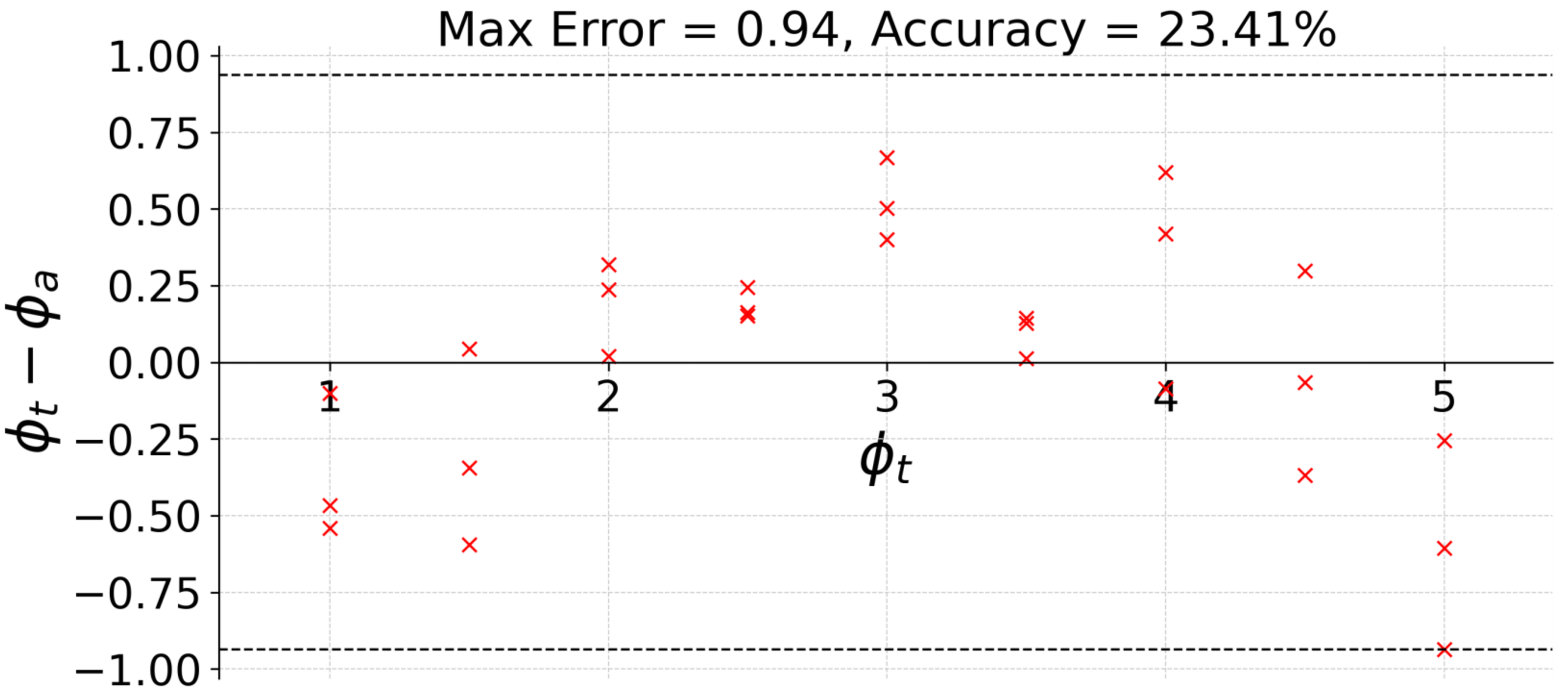


Sensor static characteristics

Accuracy

- A measure of the difference between the true value and the actual value.
- Usually expressed as a percentage of the full-scale value of the measurand.





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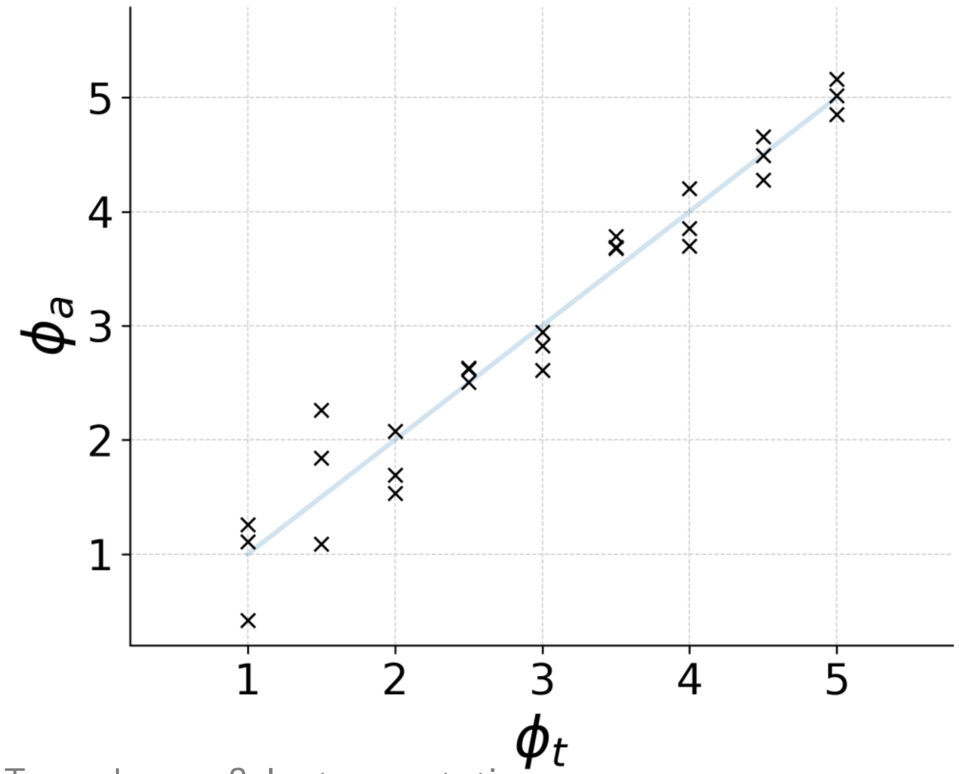
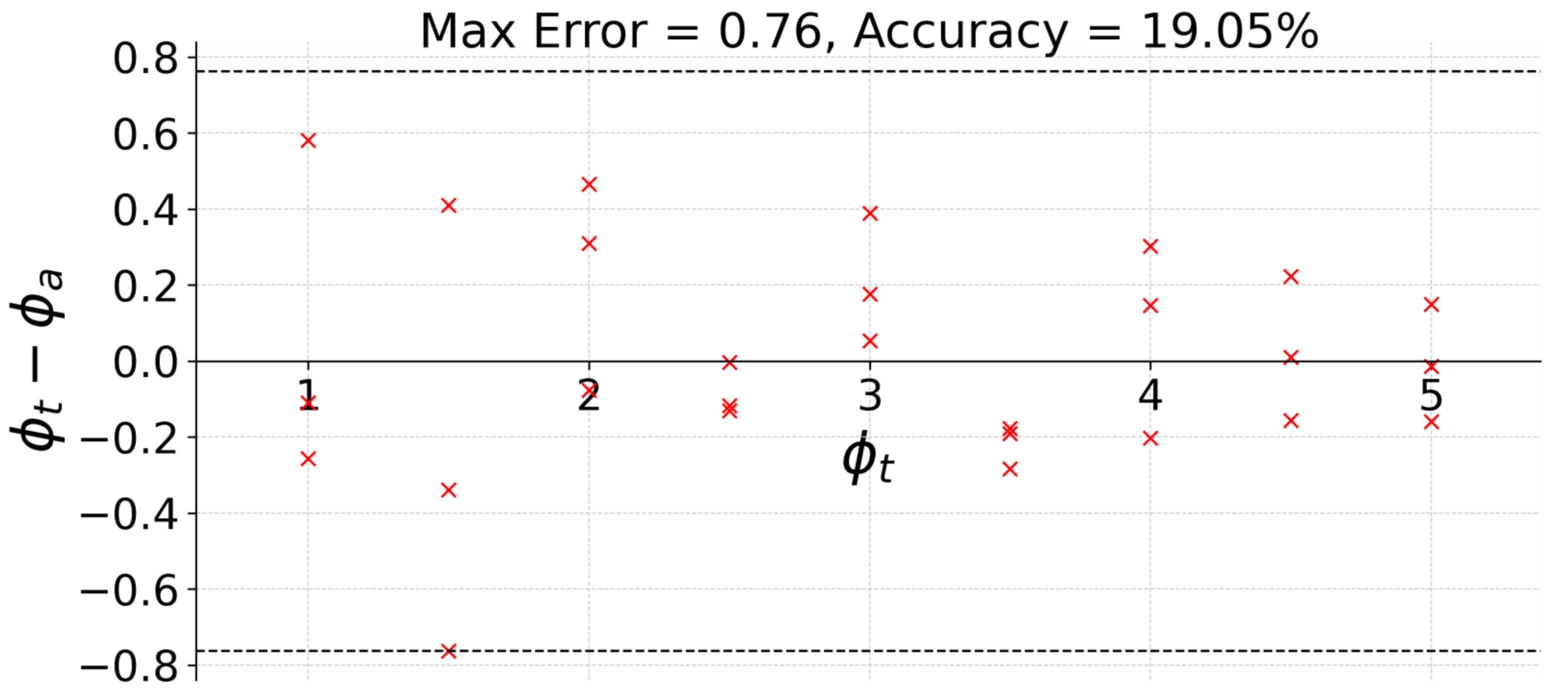
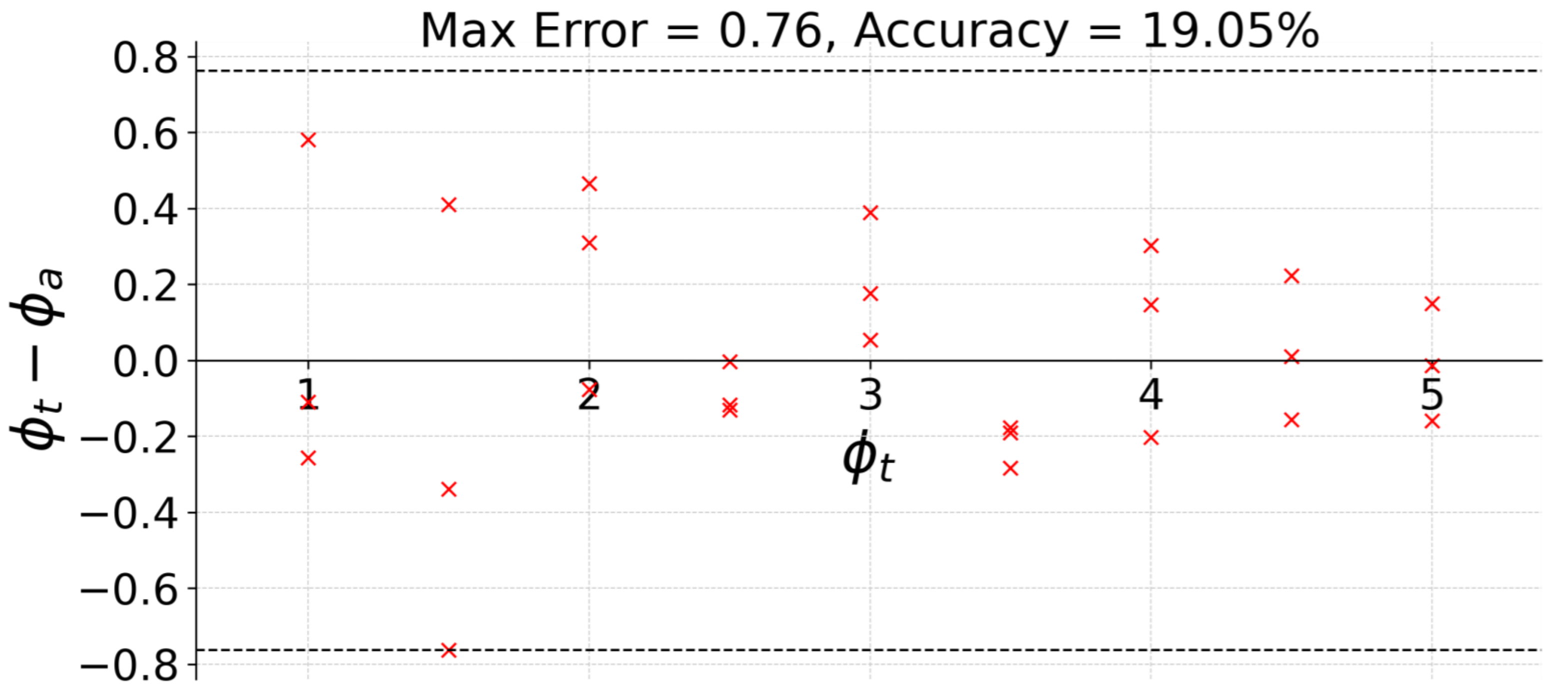




Sensor static characteristics

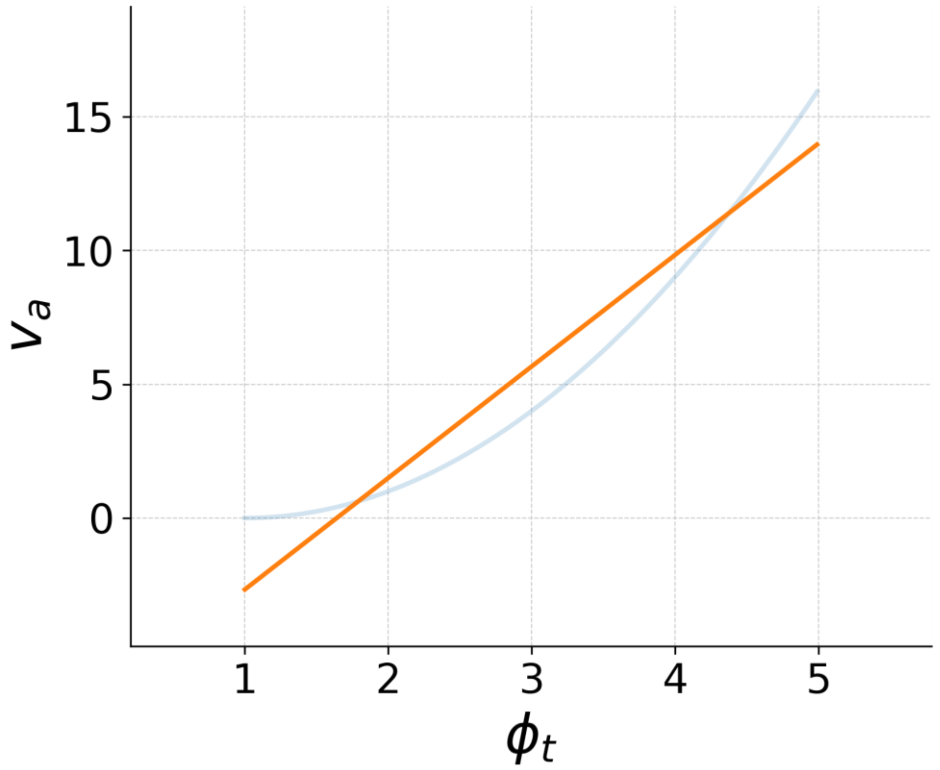
Precision

- A measure of repeatability of the sensor output.



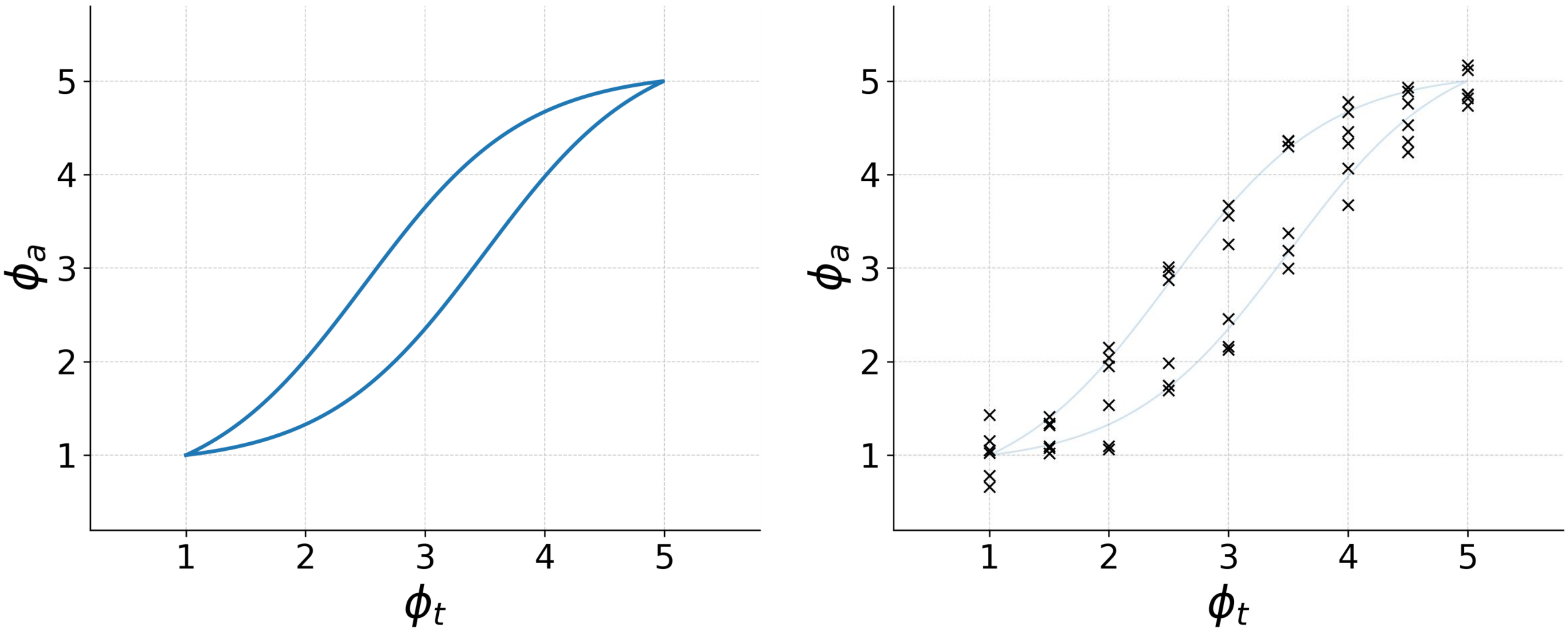
Sensor static characteristics

Linearity



Sensor static characteristics

Hysteresis



Sensor static characteristics

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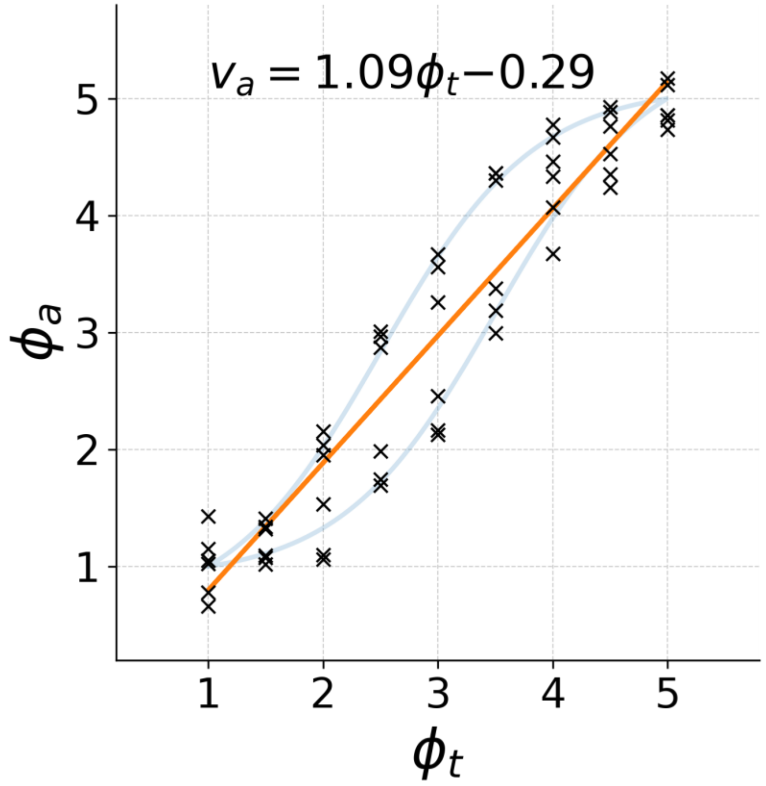
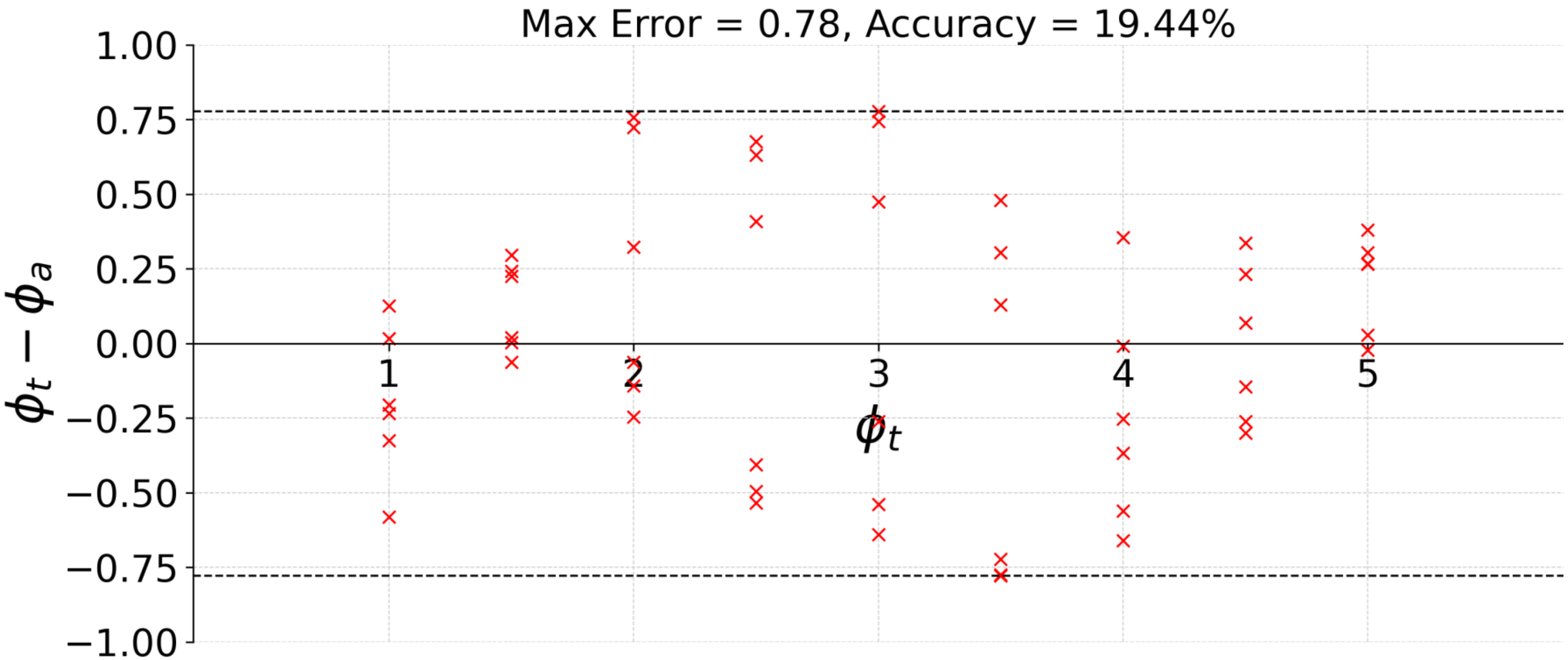
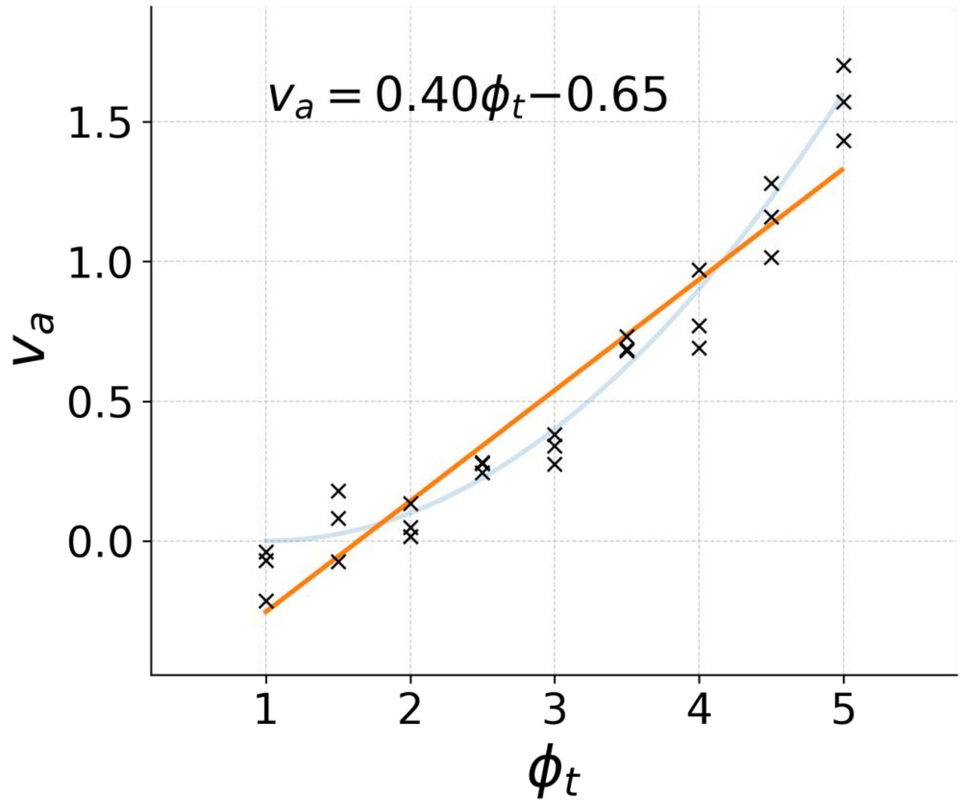


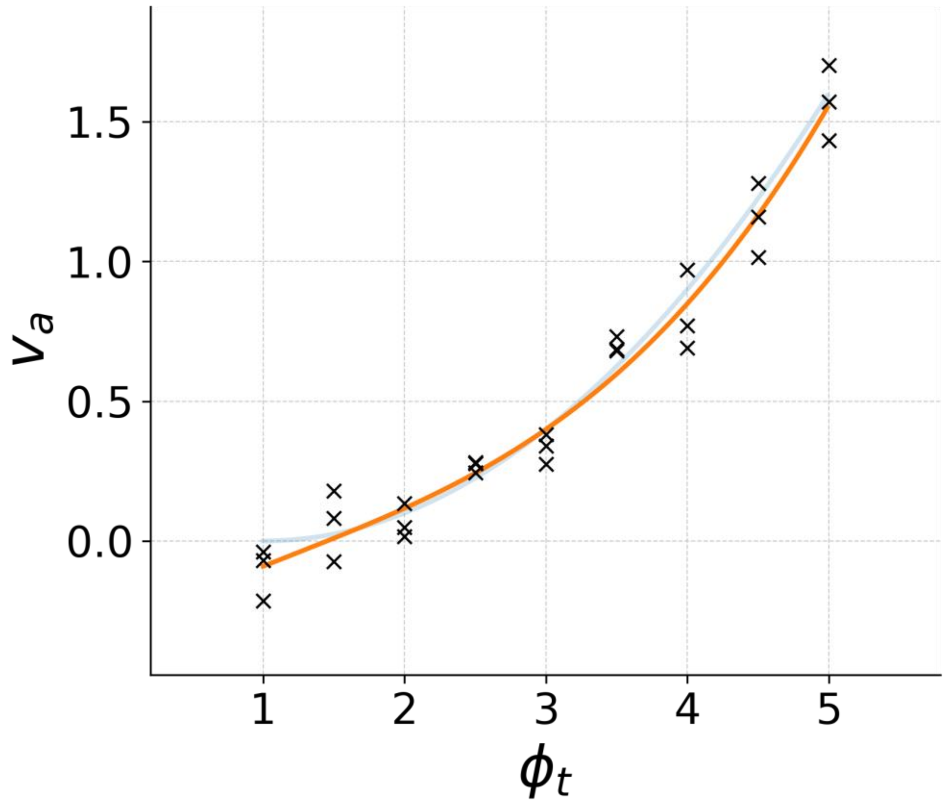


Sensor static characteristics

- Static sensitivity.

$$y = f_d(x_d, x_m) + f_i(x_i, x_m) + \varepsilon \quad \rightarrow \quad \frac{\partial \boldsymbol{f_d}(\boldsymbol{x_d}, \boldsymbol{x_m})}{\partial \boldsymbol{x_d}}$$





Sensor static characteristics

- Zero drift and Sensitivity drift