6 - Line Detection & Estimation

Robotics and Computer Vision
BPC-PRP

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Brno University of Technology
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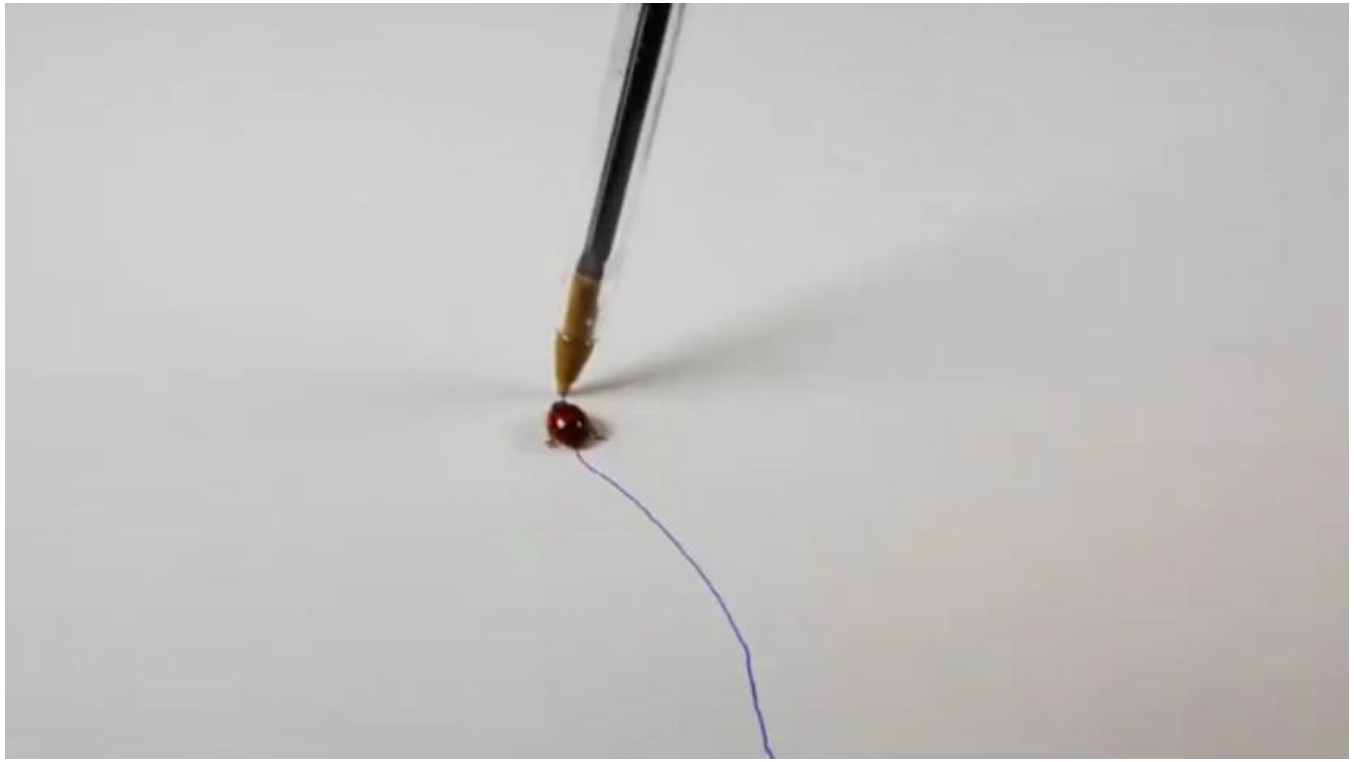
Motivation

„Ladybugs use their sense of smell to follow paths. Robots don't have a sense of smell – but they have sensors. With just one small sensor, we can make a robot that follows lines just like a ladybug.“



1. NiceSplash. *„Ladybug Follows Line“.* Youtube, 2020. [online]. Available: https://youtu.be/MVRf0JYVPYo?si=hDKvryX3e6J-bInF

Motivation

- Used in various industries – warehouses, healthcare, ...
- Today, hybrid robots are more common
  - combining more sensors - QR following, LiDAR, IMU, etc.

What will we learn today?

- **Line detection** – Is there a line?
- **Line estimation** – Where exactly the line is?
- **Sensors** (especially TCRT5000 Sensor)
- **Signal Processing & Calibration**

Next Lecture:

- **Line Following** – How do the robot move along the line?

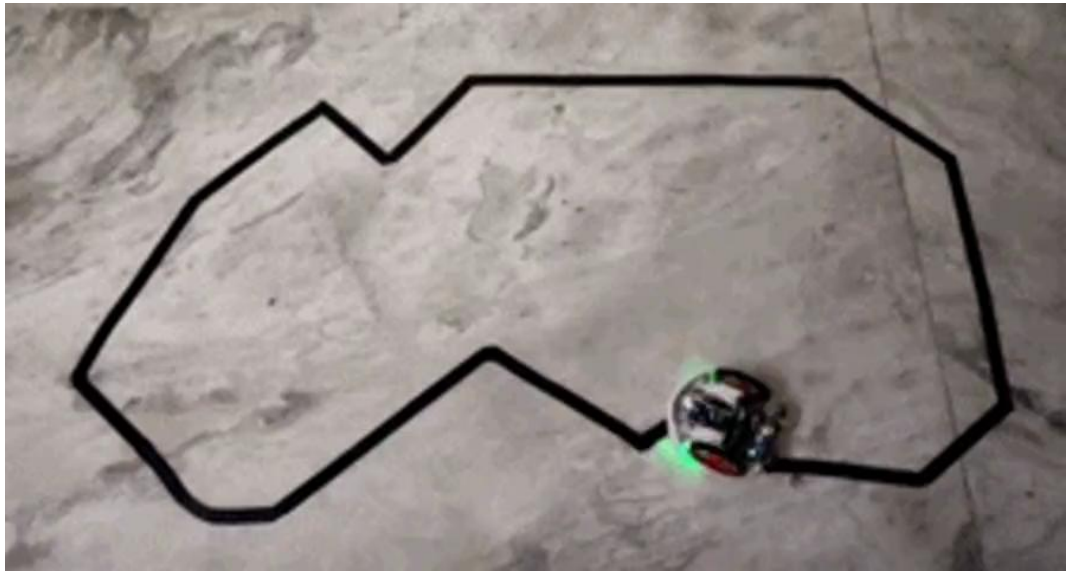
1. Davemcred. *„Insect versus Pen“.* Youtube Shorts, 2018. [online]. Available: https://www.youtube.com/shorts/DGYgW8g6j28

How do robots see lines?

Key concepts of sensors used for line detection, with a main focus on the TCRT5000 module.

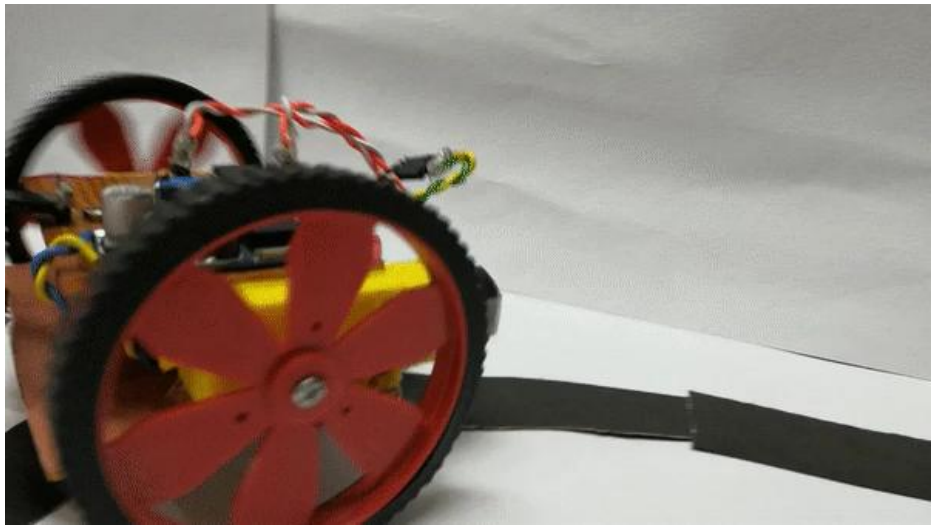
Sensors for Line Detection

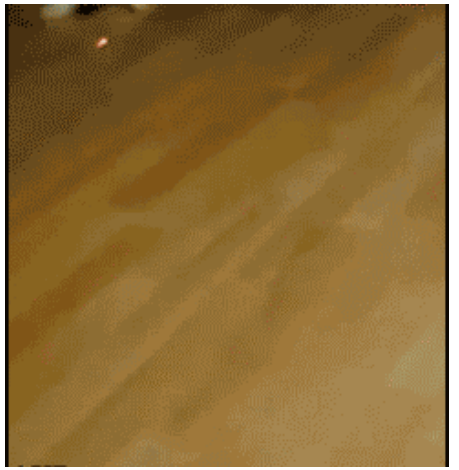
- Two Main Categories of Line Detection Sensors (Based on Detection Method):
  - Reflection-Based Sensors
  - Vision-Based Sensors



Reflection-Based Sensors

- Measuring the amount of **light reflected from the surface**
- Typically use **emitter** (LED) and **receiver** (photodetectors)
- **Types**:
  - **IR Sensors** – detects contrasts using IR light (e.g. TCRT5000)
  - **Optical Sensors** – similiar, but using visible light
  - **Color Sensors** – detect specific colors rather than just contrast
- **Advantages**:
  - Simple and cost-effective
  - Fast response time
- **Disadvantages**:
  - Affected by ambient light or surface reflection
  - Cannot detect complex patterns or intersections

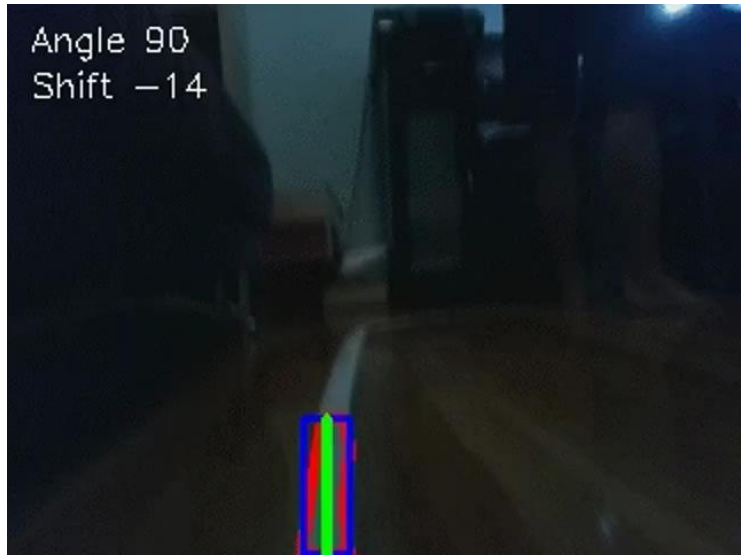




1. Neutrino-1. „*LIR Based Line Following Robot From Scratch*“. Autodesk Instructables, 2019. [online]. Available: https://www.instructables.com

Vision-Based Sensors

- Uses **cameras**
- Analyze contrast, color, or patters in the image
- Basic Camera systems (CMUcam) or Advanced Vision systems with AI (**OpenCV**)



- **Advantages**:
  - detect complex lines, curves or intersections
  - Works in various lighting conditions
- **Disadvantages**:
  - Computationally expensive
  - Good processing power and algorithms

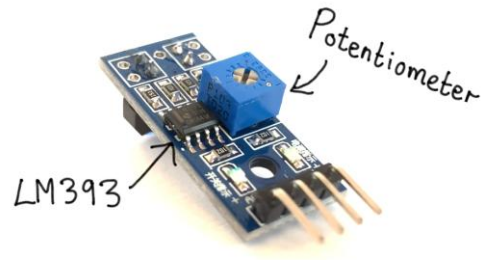
1. Toporov, C.. „*Line following robot with OpenCV and contour-based approach*“. Medium, 2018. [online]. Available: https://const-toporov.medium.com
2. CRM-UAM, „*VisionRace*“. GitHub Repository, 2019. Available: https://github.com/CRM-UAM/VisionRace

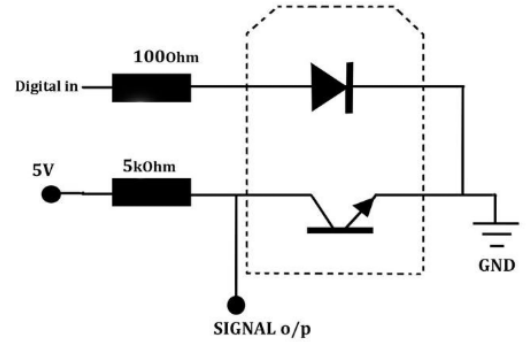
Understanding the TCRT5000 Sensor

Understanding the working principle of the TCRT5000 infrared sensor, its limitations, and how to improve accuracy through calibration.

TCRT5000 sensor

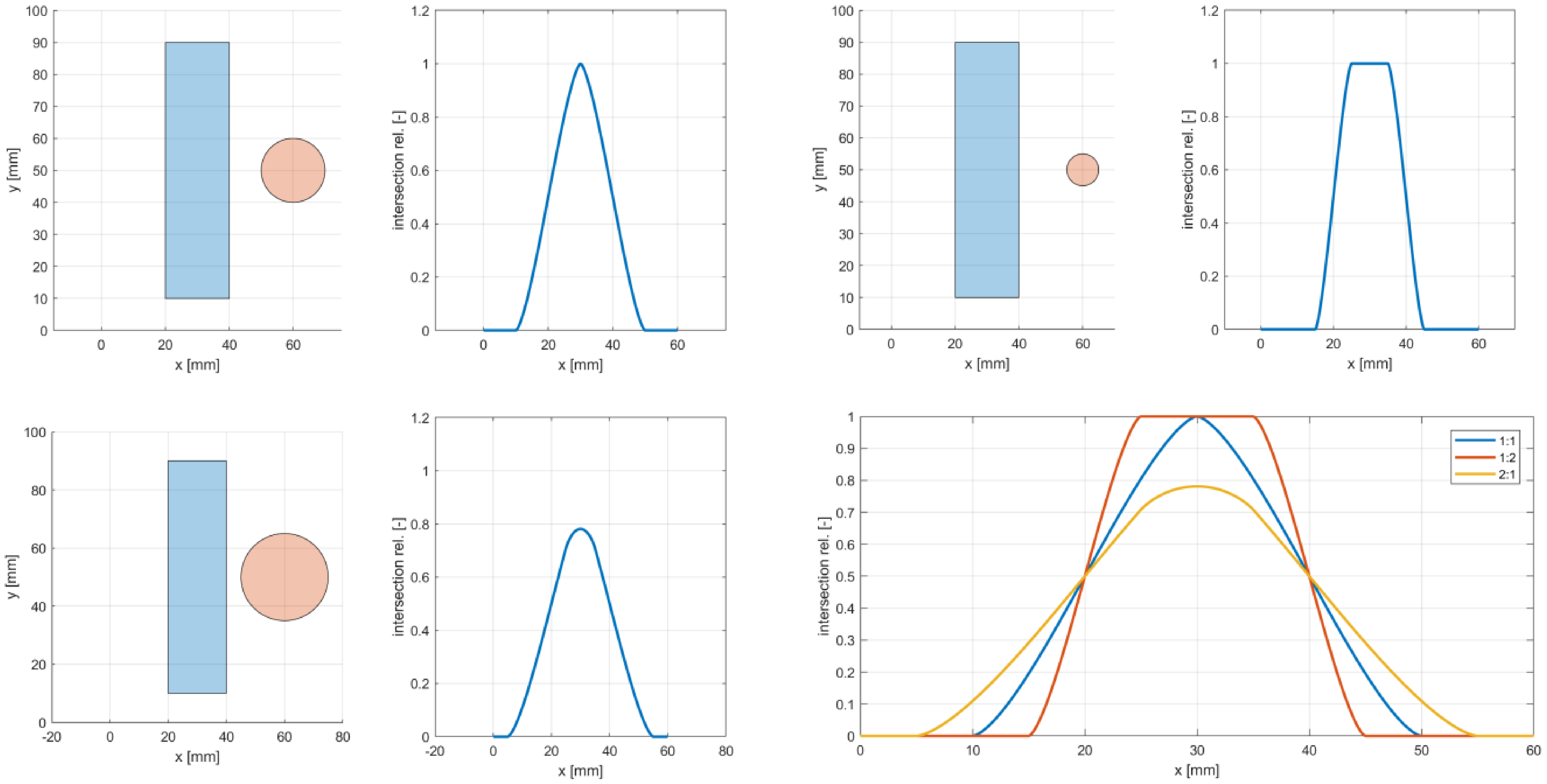
- Infrared reflective sensor
- used for line detection, proximity sensing, and object detection
- **Consists of:**
  - **IR LED** – emits infrared light
  - **Phototransistor** – detects the intensity of reflected IR light
  - (**Potenciometer & LM393 comparator** – Used only with Digital output)
- **The outputs**:
  - Analog - proportional to reflectivity
    - Provides finer details – allowing estimation of the line‘s exact position
    - Higher Voltage == more IR light recieved
  - Digital – treshold-based decision
- Does **NOT have its own ADC** – used external (Arduino)





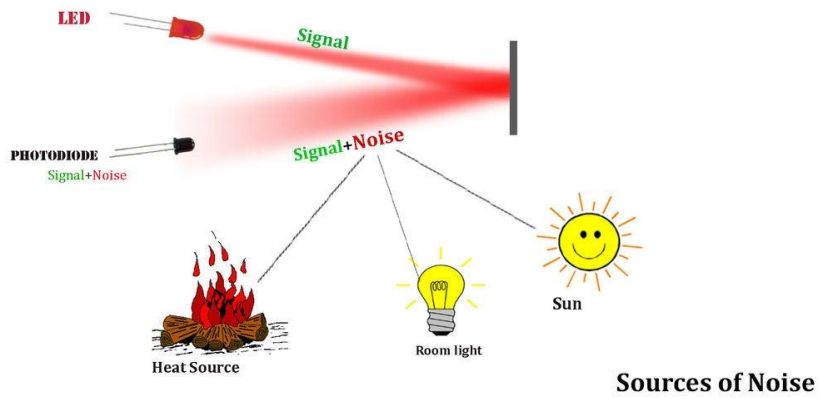
1. DIY Machines, „*TCRT5000 Infrared Reflective Sensor- How It Works and Example Circuit With Code*“. Autodesk Instrictables, 2019. [online]. Available: https://www.instructables.com
2. Vishay, „*TCRT5000 Reflectiive Optical Sensor Datasheet*“. Vishay Intertechnology, 2020. [online]. Available: https://www.hwkitchen.cz/user/related_files/infra-senzor-tcrt5000.pdf
3. Abhilashpatel121, „*Using IR Sensor (TCRT5000) with Arduino“.* Project Hub, 2020. [online]. Available: Using IR Sensor (TCRT 5000) With Arduino | Arduino Project Hub

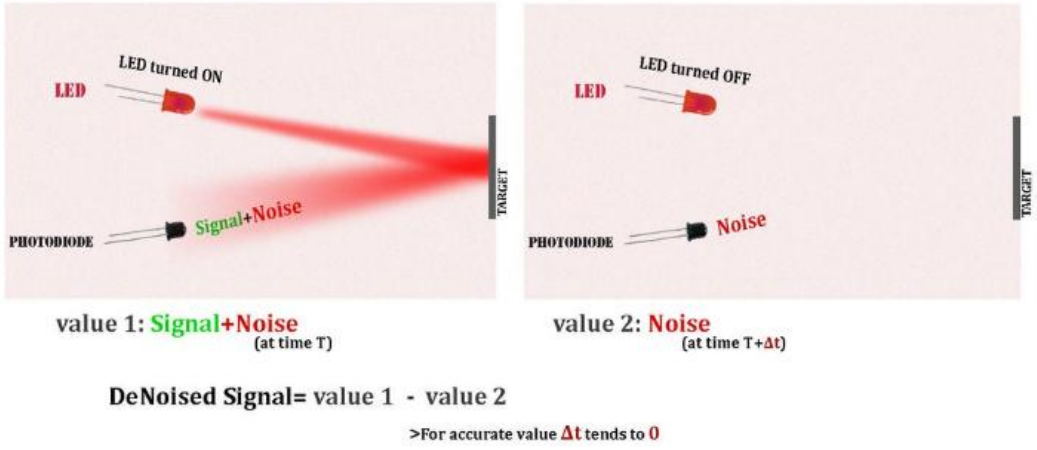
Sensor Response to Line Position – Theoretical Models



TCRT5000 sensor – Parasitic Effects

- Parasitic influences can lead to incorrect readings or unstable behavior
- **Key factors:**
  - **Ambient Light Interference**
    - External IR sources (Sunlight or other IR Emitors)
  - **Distance from the Surface**
    - Too far – reflected IR signal weakens
    - Too close – phototransistor can saturate
  - **Surface Material & texture**
    - Transparent or glossy surfaces are problematic
  - **Thermal Drift**
    - Sensitivity to temperature changes
  - **Electival noise & Power Supply Stability**
  - **Aging & Component Variablity**
    - No two sensors are exactly the same





1. Abhilashpatel121, „*Using IR Sensor (TCRT5000) with Arduino*“. Project Hub, 2020. [online]. Available: Using IR Sensor (TCRT 5000) With Arduino | Arduino Project Hub

TCRT5000 sensor – Calibration

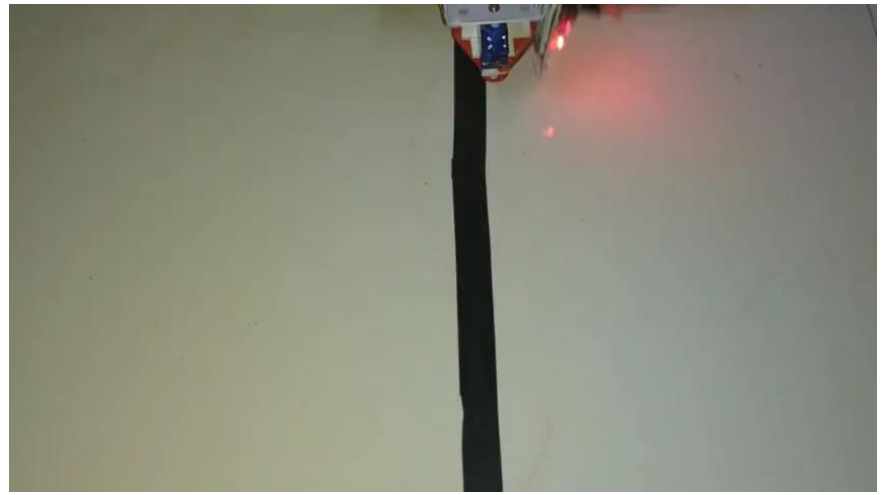
- Ensures the **sensor is correctly adapted to the environment and provides reliable data.**
- **Basic Concept:**
  - Determining the minimum and maximum sensor response value when placed over different surfaces (black & white)
- **Types of Calibration:**
  - **Static (manual)**
    - **Fixed threshold is set** based manual measurment
    - Sensor does not adjust to enviromental changes
  - **Dynamic (Automatic)**
    - Continuously updates values – **adapting to changes**
    - Robust but additional computation
  - **Multi-Sensor (used multiple sensors)**
    - Each sensor must be calibrated individually

Line Estimation

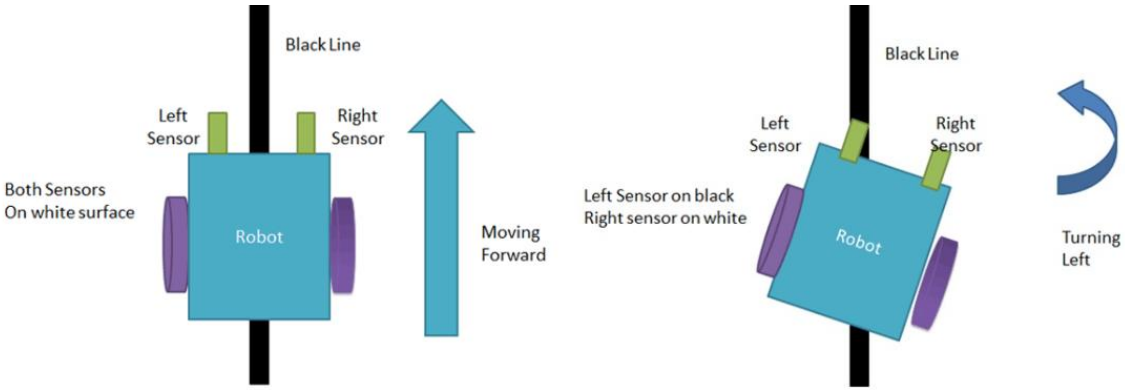
Using Multiple Sensors to Estimate the Robot’s Position on a Line

Line estimation - introduction

- **Single sensor:**
  - Line detection – detects the presence of the line
  - Limited transfer characteristic – Uses only half of the sensor's response range
  - Edge detection only – Can detect the edge of the line but not its exact position.
  - Sensitive to noise



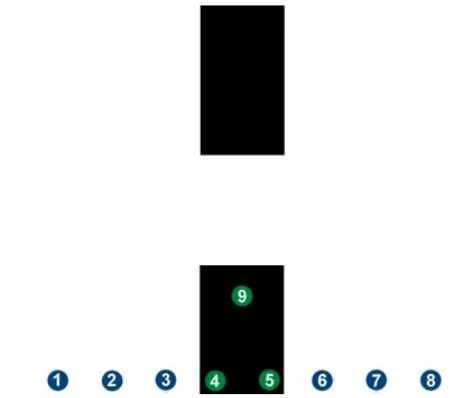
- **Multiple sensors:**
  - Line estimation – can estimate the position of the line
  - Many approaches:
    - Binary Detection Approach
    - Primary & Correctional Sensor Approach
    - **Differential Approach**
    - Interpolative Approach



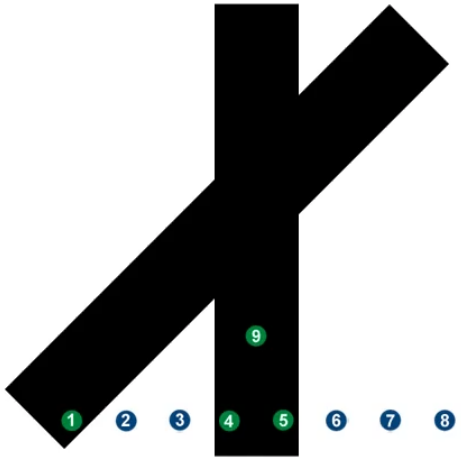
1. Engineerkid1. *„Line Follower Robot Using Only One IR Sensor".* Autodesk Instructable. [online]. Available: Line Follower Robot Using Only One IR Sensor : 5 Steps - Instructables
2. Saddam. *„Line Follower Robot using 8051 Microcontroller".* Circuit Digest, 2015. [online]. Available: Line Follower Robot using 8051 Microcontroller: Project with Circuit Diagram & Code

Multiple Sensors – Binary Detection Approach

- Mostly used **row of digital sensors** – black/white (0/1)
- Position is estimated as average index of all active sensors or using rule-based approach



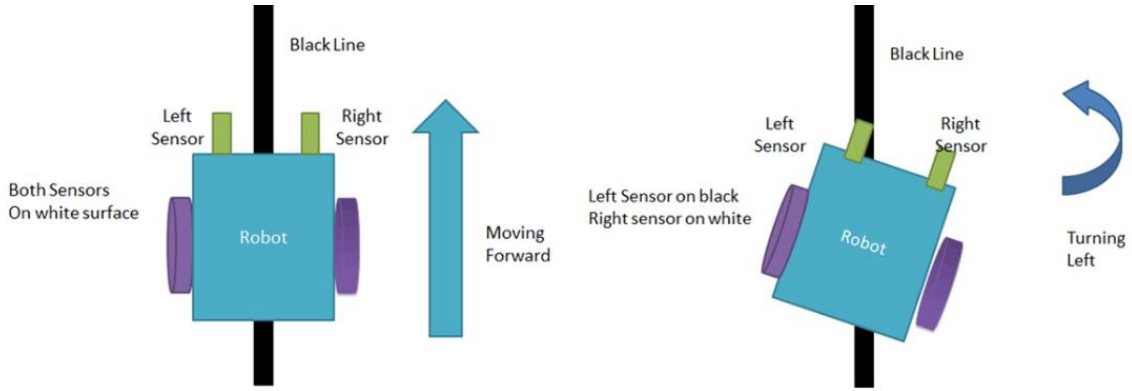
- **Advantages:**
  - Simple implementation
  - Fast data processing
- **Disadvantages:**
  - Low accuracy
  - Rapid movement may cause incorrect line detection (jumping between sensors)



1. Midhun_s. *„Robot – Line Follower“.* Autodesk Instructables, 2014. [online]. Available: Robot - Line Follower : 35 Steps (with Pictures) - Instructables

Multiple Sensors – Primal & Correctional Approach

- One sensor (layer) acts as the **primary sensor**
  - main reference for detecting the line
- The second sensor (layer) acts as a **correctional sensor**
  - Adjusting the estimated position (fine-tuning)

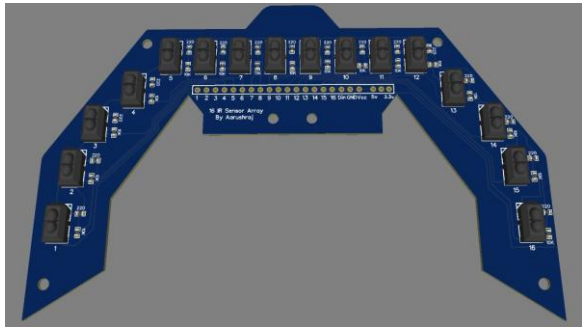


- **Advantages:**
  - Need stability and robustness
  - Handling gradual deviations smoothly
  - Combination with advanced filtration methods
- **Disadvantages:**
  - Limited Precision
  - Issues with Line Gaps & Intersections – rquire runing of correction coefficients
  - Higher complexity of connection and data processing - Slow Response to Fast Changes

1. Saddam. *„Line Follower Robot using 8051 Microcontroller“.* Circuit Digest, 2015. [online]. Available: Line Follower Robot using 8051 Microcontroller: Project with Circuit Diagram & Code

Multiple Sensors – Interpolative Approach

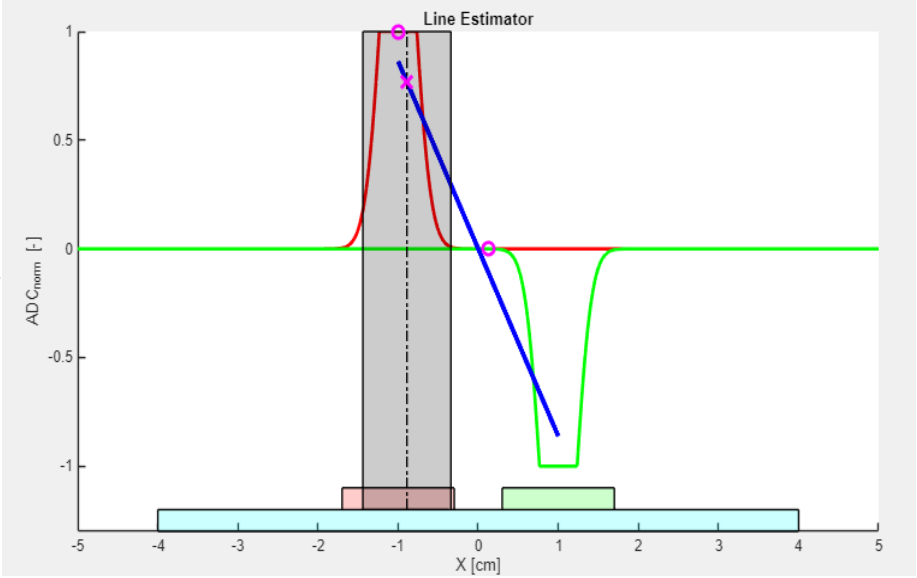
- The recommended number of sensors is 5 or more
- Each sensor contributes equally to estimate exact location
  - For certain part of the resulting measuring range of the sensor system
- Main point is interpolation (linear, parabolic or Spline) between readings to get smooth position estimation
- Can be used dynamic calibration for each sensor
- **Advantages:**
  - Most accurate method
  - For wider lines too
- **Disadvantages:**
  - High computational cost



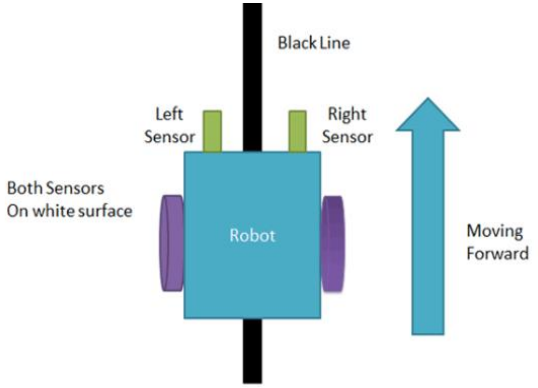
1. Kakarobot. *„Two robot Kakarobot in final competition“.* Youtube, 2023. [online]. Available: Two Robots Line Follower Kakarobot in same race

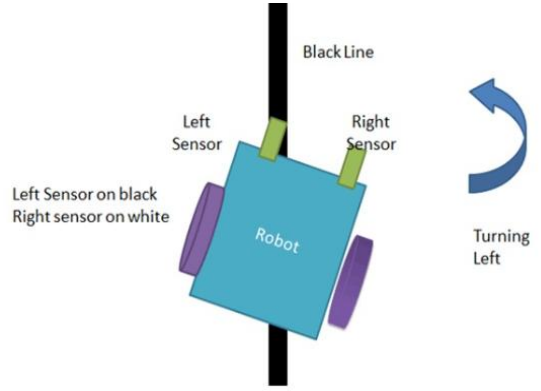
Multiple Sensors – Differential Estimation

- Uses two analog sensors placed at fixed distance part
- Based on the difference in responses between the 2 sensors
- The sensor characteristic is nonlinear – it is usually necessary to linearize and adjust the values.



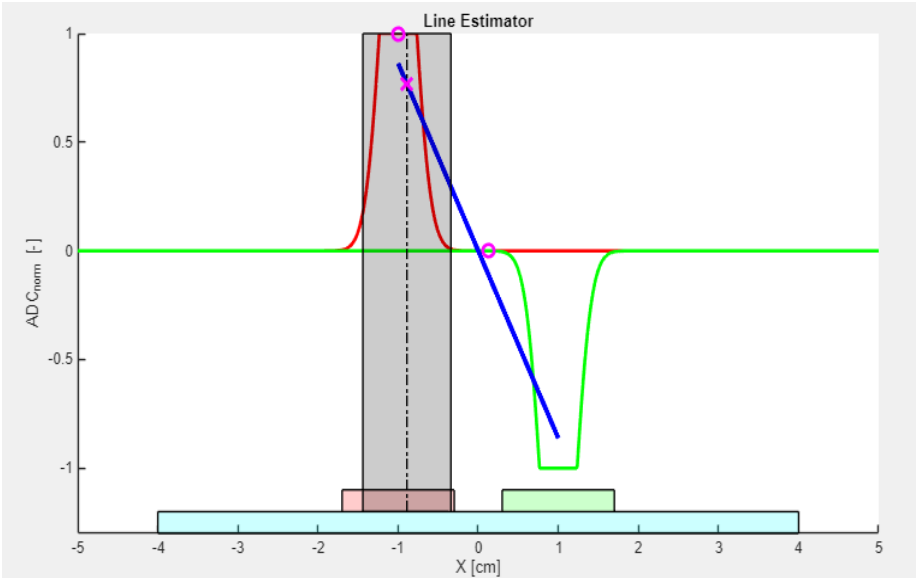
- **Advantages:**
  - Smooth transition between values
  - Higer accuracy
- **Disadvantages:**
  - Works only for narrow lines (line between sensors)
  - Method fails when the line disappears from both sensors
  - Poor perform in sharp turns





Differential Estimation - methodology

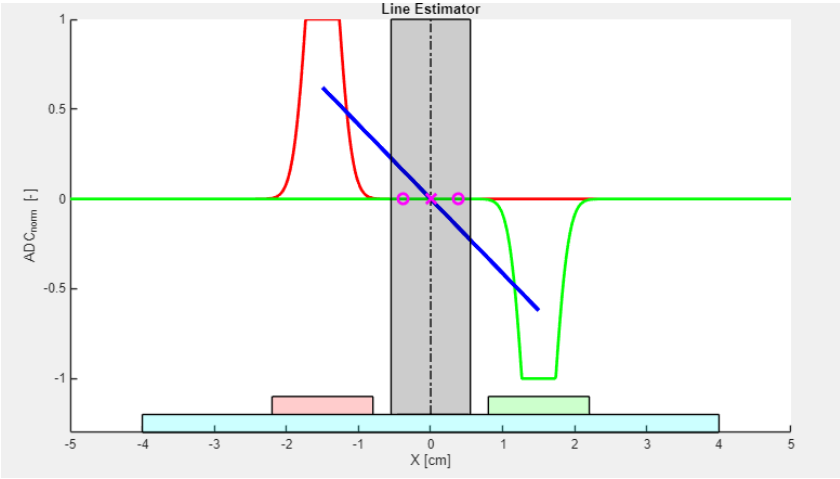
- **Methodology:**
  - 1) Invert one sensor response (to make the signals comparable)
  - 2) Normalize the ADC values to the range ⟨-1;1⟩ (if not already done).
  - 3) Linearize the sensor response (e.g., using the least squares method).
  - 4) Estimate the line position based on both sensor readings using the linearized model.
  - 5) Compute the differential signal to determine the exact line position.



- If the sensor response is nearly linear, you do not need to linearize it
- Every additive error must be compensated somewhere – „Control works like magic… until it doesn’t“

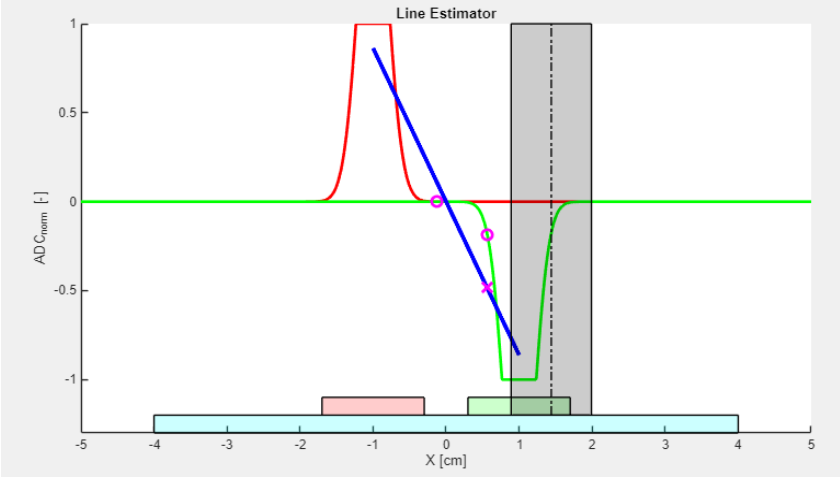
Differential Estimation - Failures

Death zone:



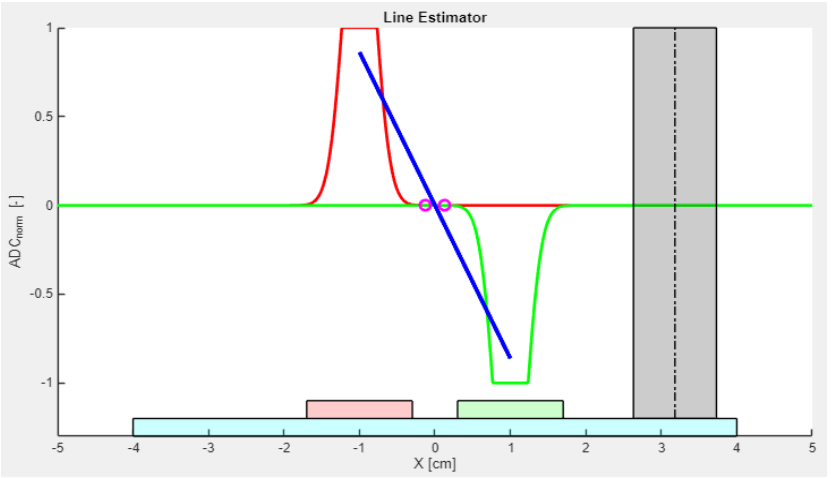
Change position of sensors

One-sided line detection:



Increase response

Out-of-range detection:



More response! MORE!! 🔥

Summary

- **Differnce between Line detection, Line estimation and Line Folowing**
- Sensors:
  - Reflection-Based Sensors
  - Visual-Based Sensors
  - TCRT 5000 module
- Line Estimation:
    - Binary Detection Approach
    - Primary & Correctional Sensor Approach
    - Differential Approach
    - Interpolative Approach

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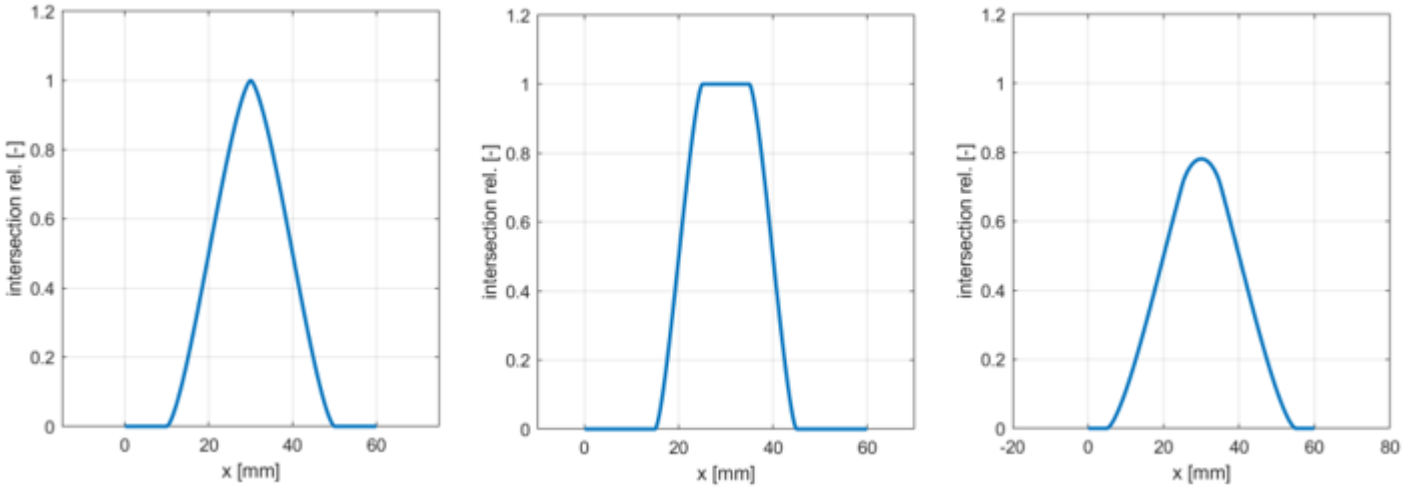
Under which conditions can we get this type of sensor response?



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Based on the ADC values, where is the line? In which direction should the robot move to stay on track?

1) $ADC_{LEFT} = 1$; $ADC_{RIGHT} = 0$
2) $ADC_{LEFT} = 0$; $ADC_{RIGHT} = 0$
3) $ADC_{LEFT} = 0.09$; $ADC_{RIGHT} = -0.01$

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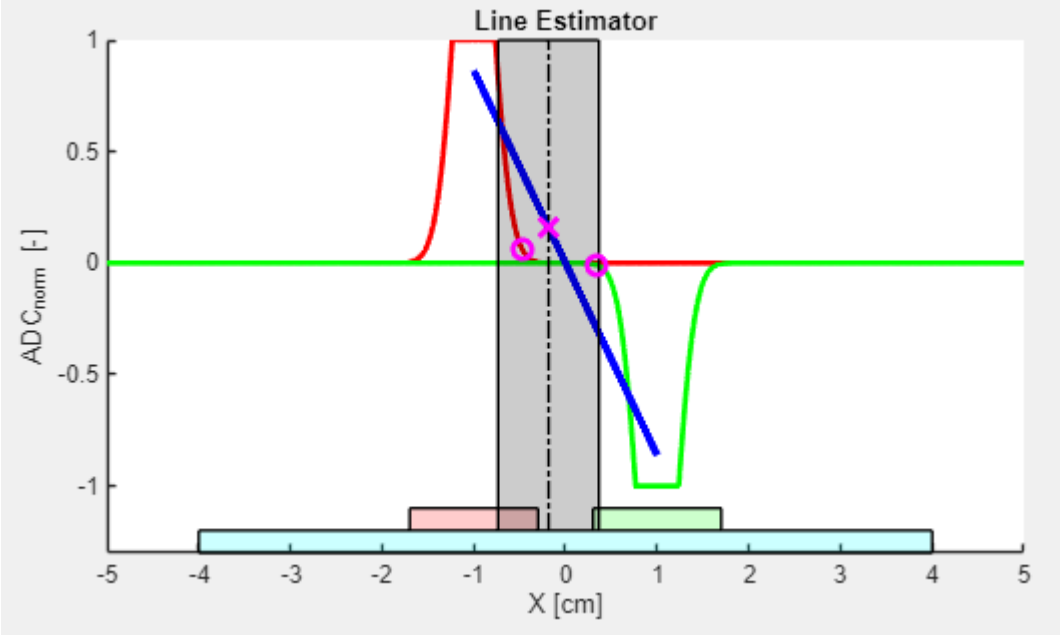

Differential Estimation - simulation

Simulator used during the lecture - Differential estimation Simulator:

https://github.com/xOrryx/DifferentialEstimationSimulator.git

(only need to download the .exe file and have Matlab Runtime 24.2 installed)

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